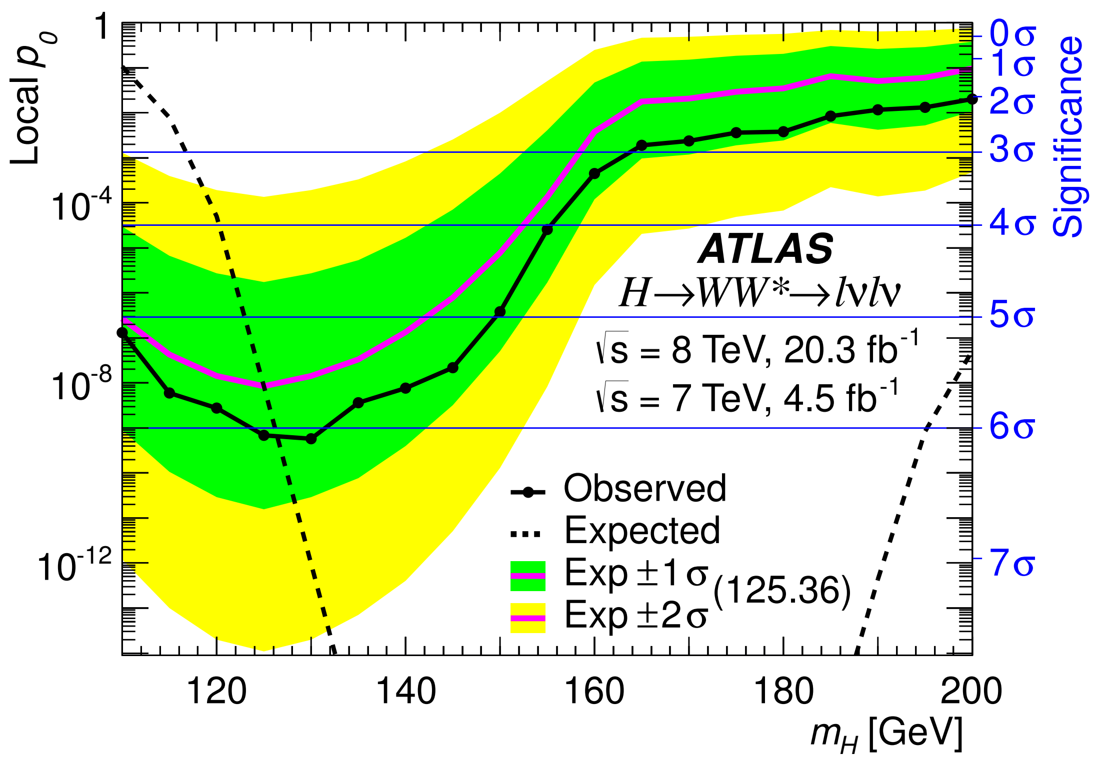
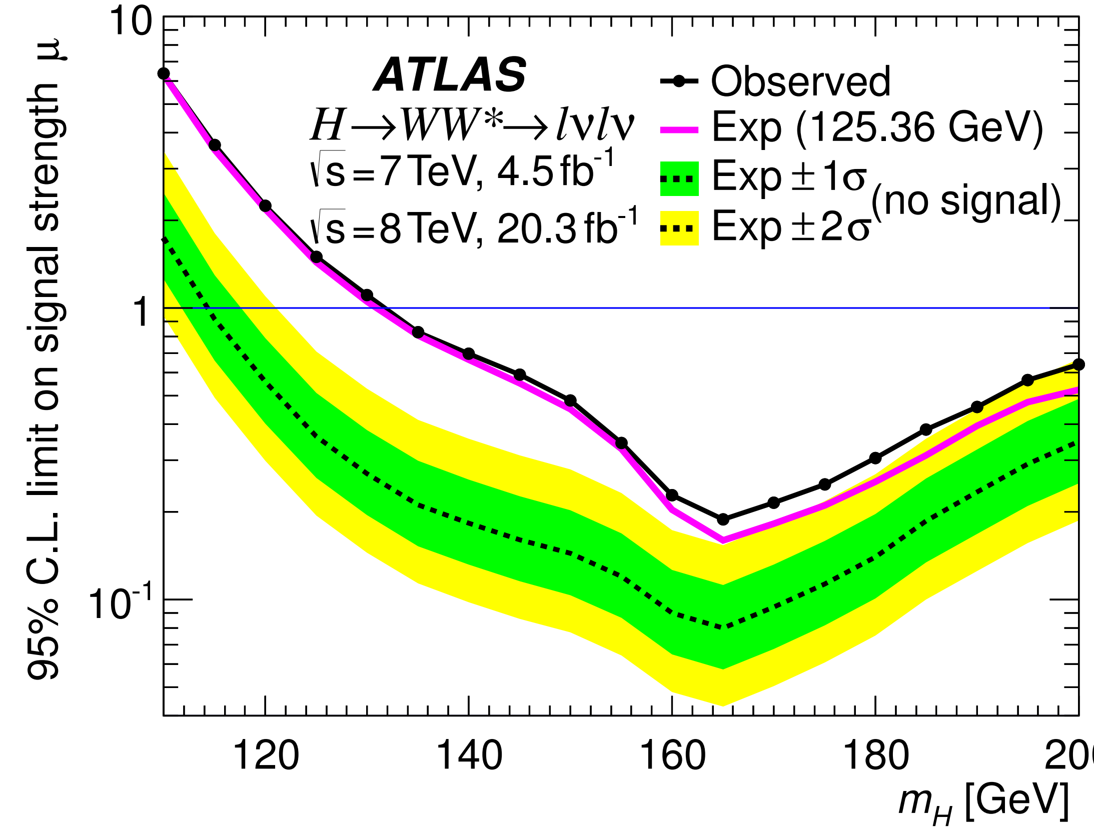
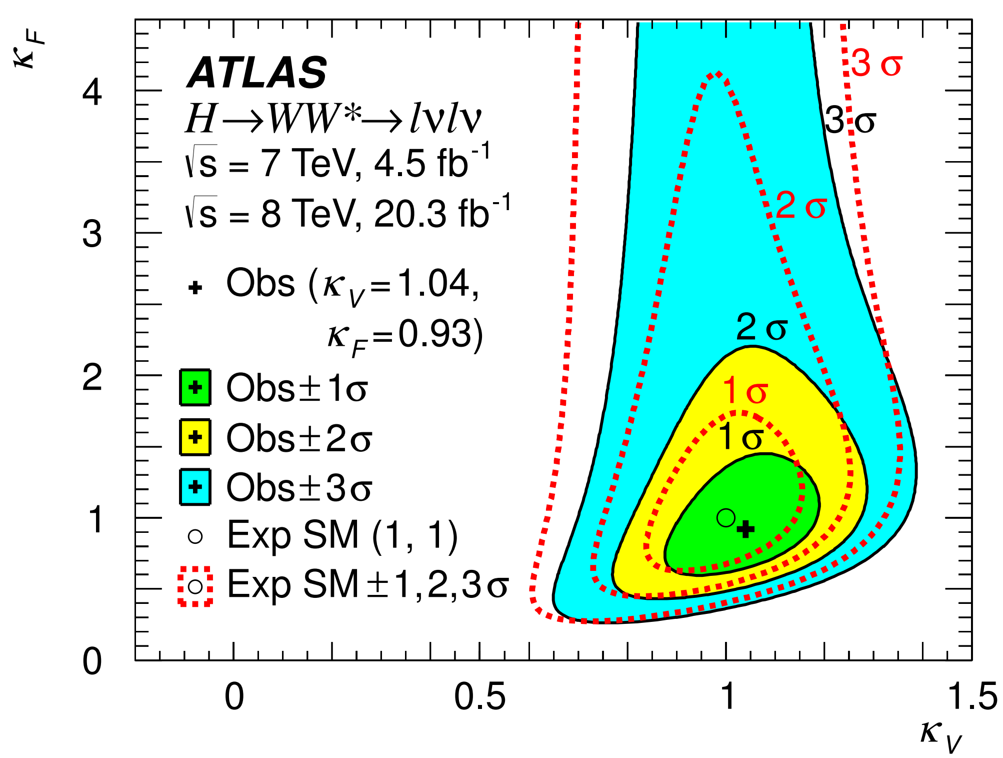
Statistical tools in Higgs search and discovery







Slides prepared using mainly material from E. Gross and W. Vekerke talks.

Introduction

Enormous effort to search for Higgs signature in many decay channels

• Results → many plots with signal, background expectations, each with (systematic) uncertainties, and data

• Q: How do you conclude from this that you've seen the Higgs (or not)?

– Want answer of type: 'We can exclude that the Higgs exist at 95% CL", or "The significance of the observed excess is 5σ"

Quantifying discovery and exclusion – Frequentist approach

• Consider the simplest case – a counting experiment
– Observable: N (the number of events)
– Model F(NIs+b): Probability to get N events given an assumed value of signal expectation (s) and background expectation (b)

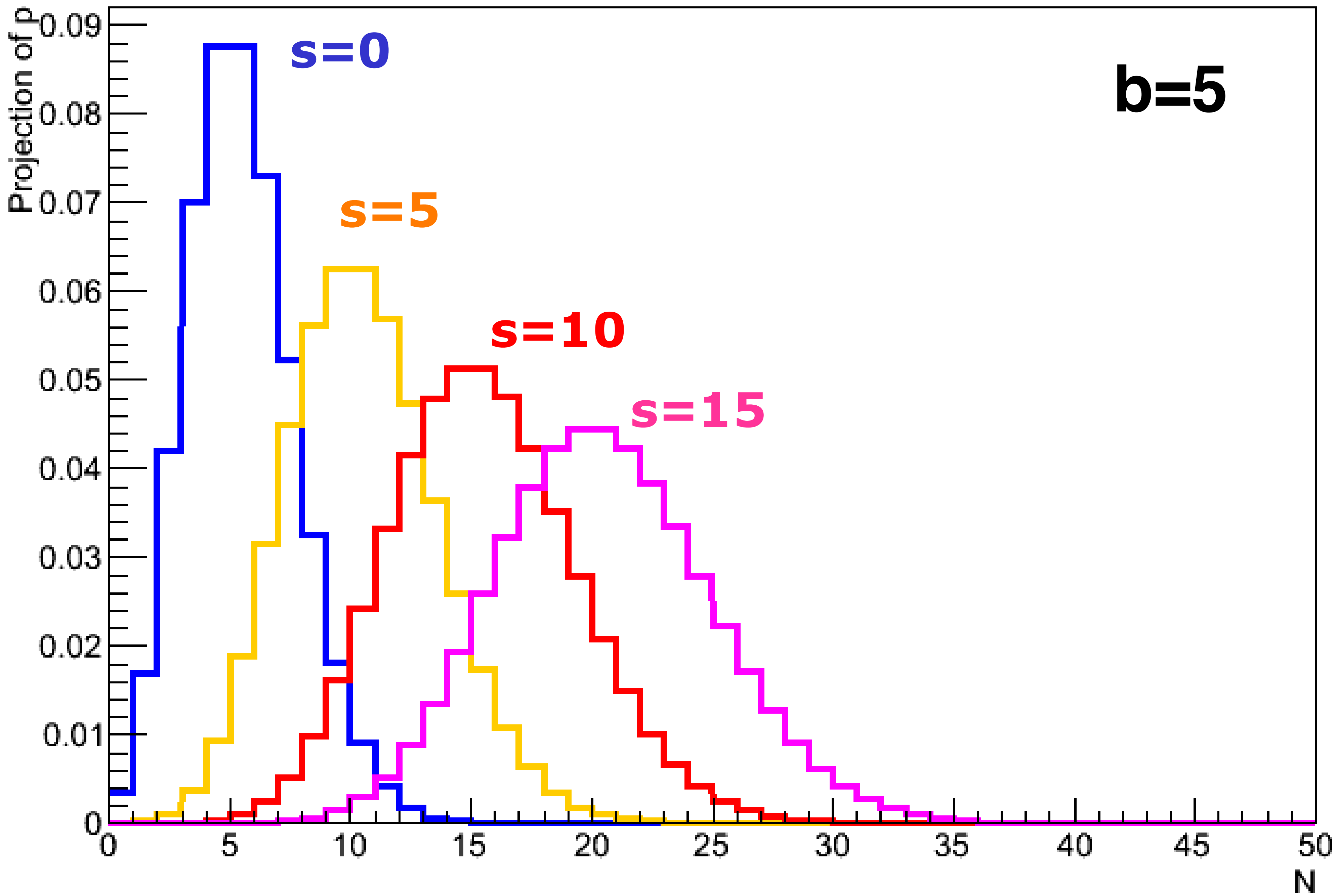
Let's assume to know exactly the expected background b=5.

F is given by Poisson(NIs+b)

$$F(N|y) = \frac{y^N}{N!}e^{-y} \Rightarrow F(N|s+b) = \frac{(s+b)^N}{N!}e^{-(s+b)}$$

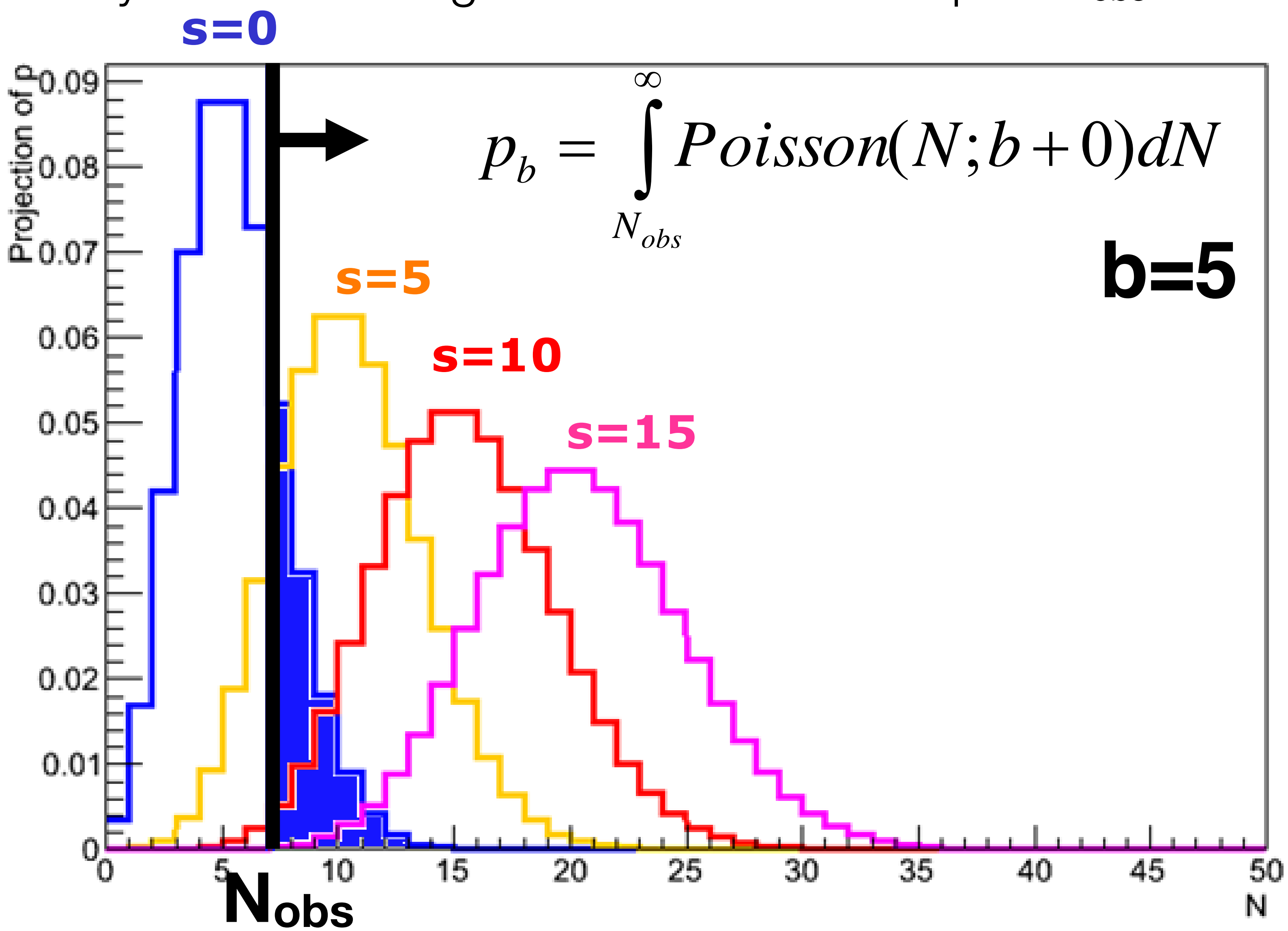
[from G.Herten]

Quantifying discovery and exclusion – Frequentist approach



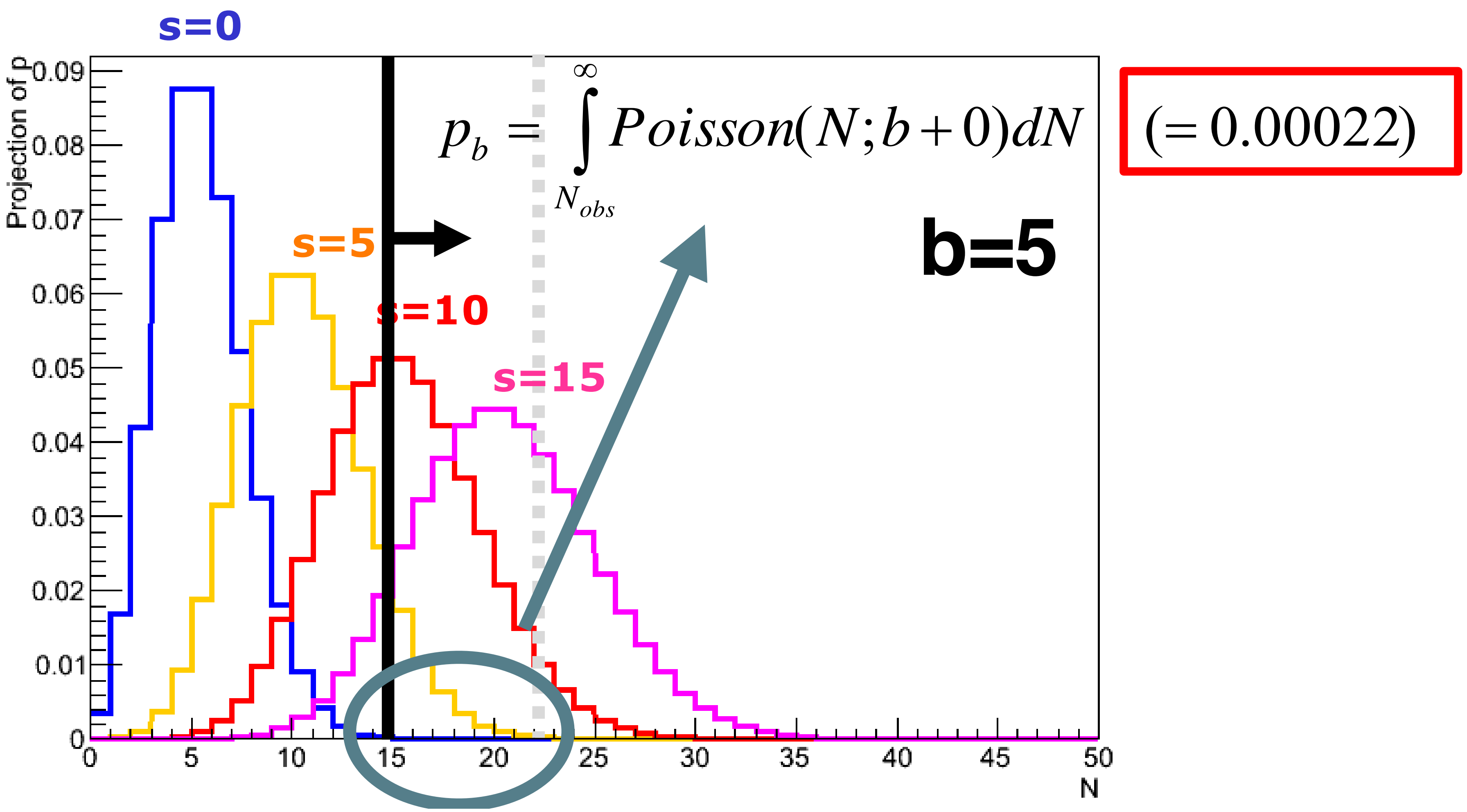
Quantifying discovery and exclusion – Frequentist approach

- Now make a measurement $N=N_{obs}$ (example $N_{obs}=7$)
- Can now define p-value(s), e.g. for bkg hypothesis
  - Fraction of future measurements with N=Nobs (or larger) if s=0
    (probability that the background can fluctuate up to N_{obs} or above)



$$p_b = \int_{N_{obs}}^{\infty} Poisson(N; b+0)\,dN \quad (=0.23)$$

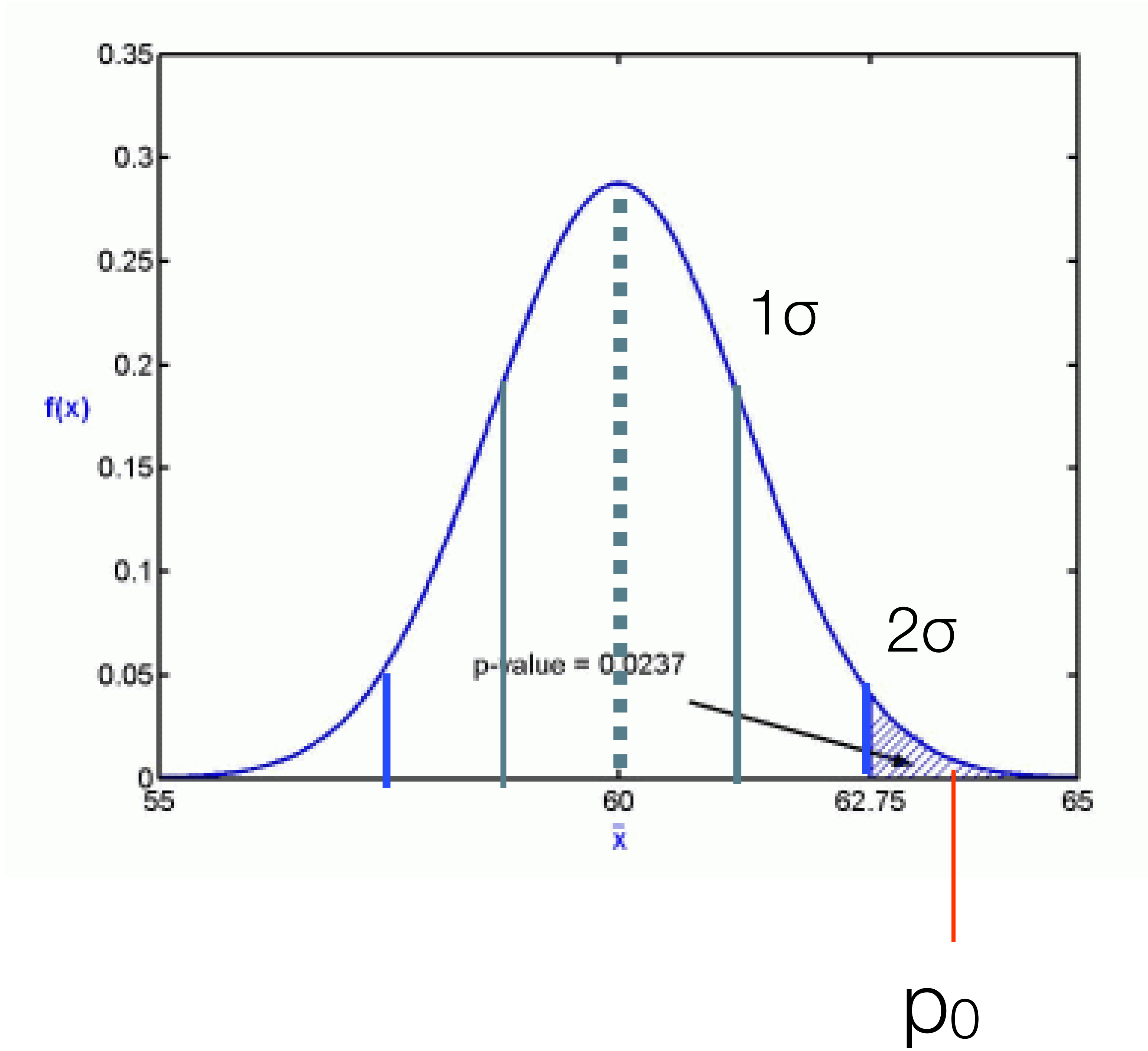
- p-values of background hypothesis is used to quantify 'discovery' = excess of events over background expectation
- Another example: N_{obs}=15 for same model, what is p_b?



For large b the Poisson distribution becomes a gaussian distribution

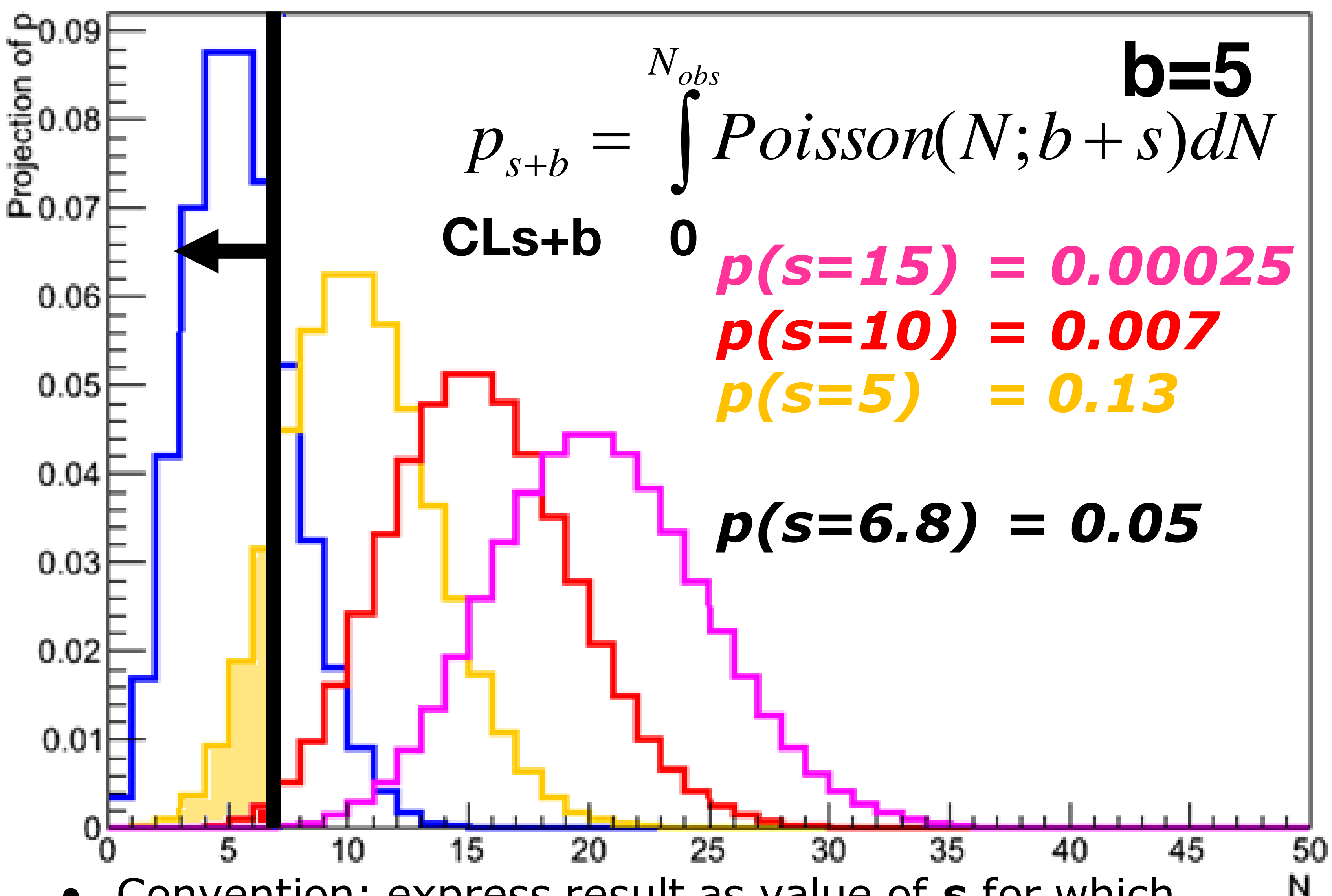
From p_0 to number of σ

An observed excess is nσ
if the integral of the right tail above the region delimited by the nσ interval is equal to the observed p_0



Quantifying exclusion – Frequentist approach

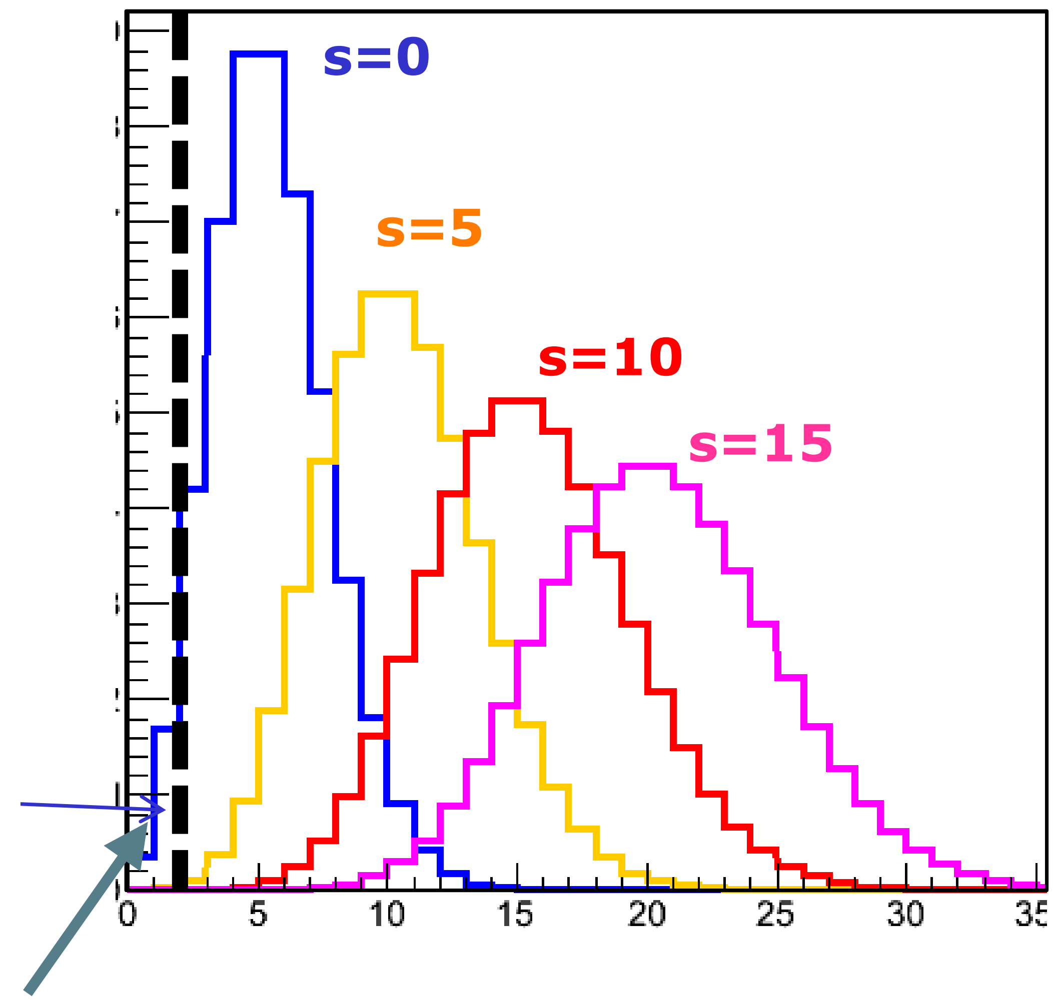
We want to exclude a signal hypothesis s.
The question is: are my data compatible with the signal+background hypothesis?
or: what is the probability that s+b under fluctuates below the observed yield N_{obs}?



- Convention: express result as value of **s** for which p(s+b)=5% → **"s>6.8 is excluded at 95% C.L."**

Small signals and background under-fluctuations

- $\langle N_{obs} \rangle = s+b$ leads to the physical requirement that $N_{obs} > b$
- A very small expected s might lead to an anomaly when N_{obs} fluctuates far below the expected background, b.
- At one point DELPHI alone had $CL_{s+b}=0.03$ for $m_H=116$ GeV
- However, the cross section for 116 GeV Higgs at LEP was too small and Delphi actually had no sensitivity to observe it
- The frequntist would say: Suppose there is a 116 GeV Higgs….
  In 3% of the experiments the true signal would be rejected… (one would obtain a result incompatible or more so with m=116) i.e. a 116 GeV Higgs is excluded at the 97% CL…..



The background hypothesis is not very likely, excluding background automatically excludes any signal

The problem of this method is that it ignores sensitivity to signal. Even if you expect s=0.000001 you would exclude any signal if your background under fluctuates.

Small signals and background under-fluctuations

$$p_b = \int_{\mathrm{N_{obs}}}^{+\infty} Poisson(N, b)dN$$

- $<N_{obs}>=s+b$ leads to the physical requirement that $N_{obs}>b$
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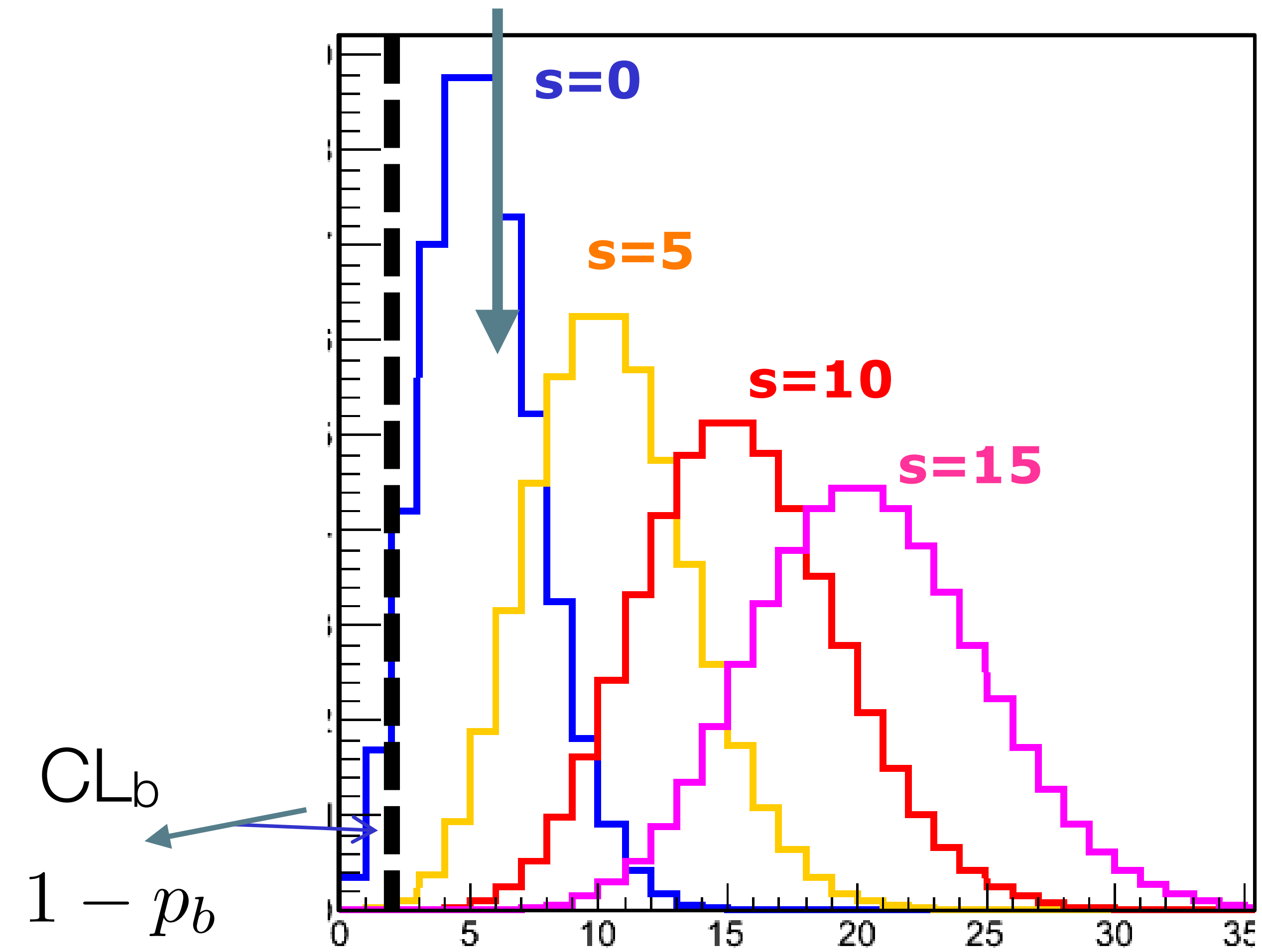


$$CL_s = \frac{CL_{s+b}}{1 - p_b}$$

if the background hypothesis is not very likely $1-p_b \rightarrow 0$ compensating the numerator

If s <<b $CL_{s+b}/CL_b \sim 1$ (no exclusion)

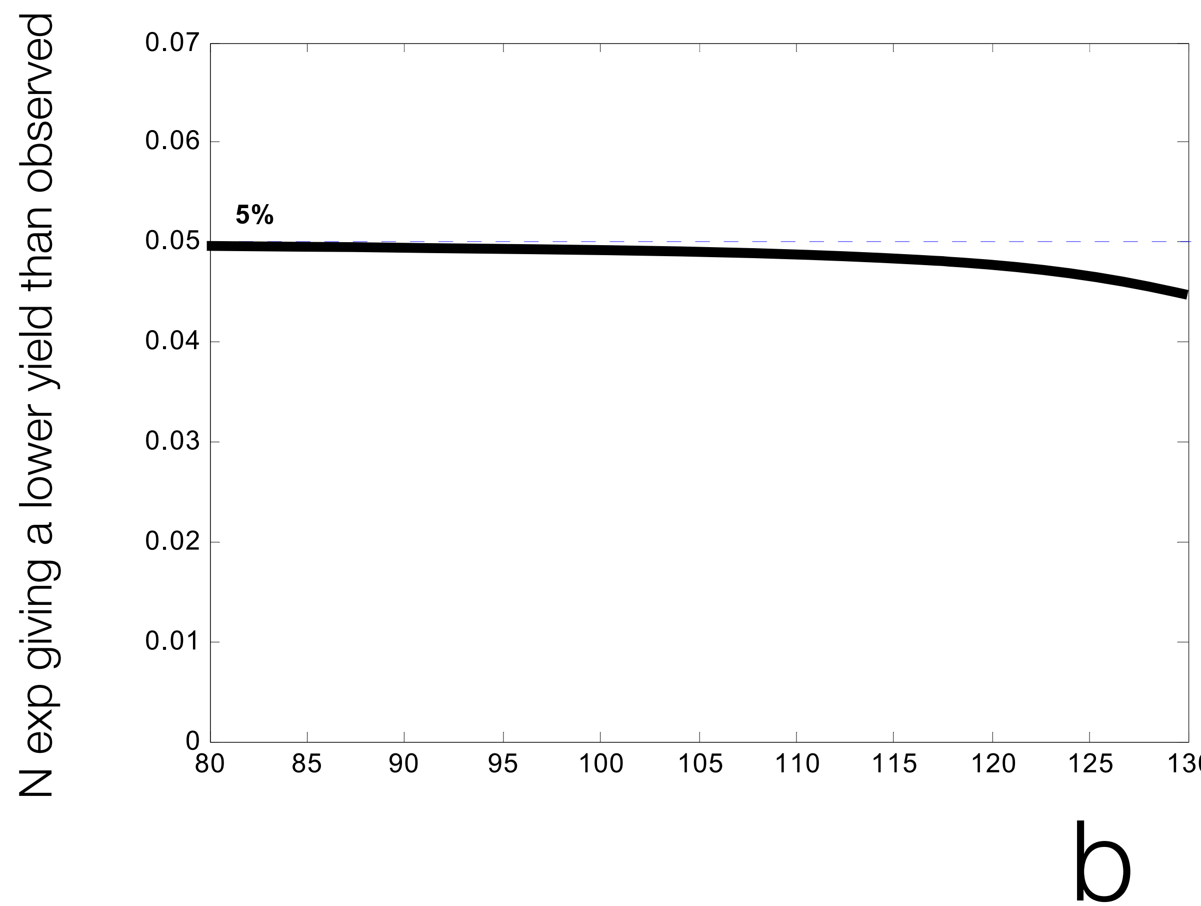
Coverage

- If we exclude a signal s at 95% C.L, we want that if we repeat the experiment may times in the s hypothesis, 95% of the times we get an event yield above the observed number of events, if such property holds we say that the C.L. is well covered
- CL_{s+b} is well covered by definition (we take the tail of the poissonian that integrates to 95% to set the 95% exclusion);
- $CL_s = CL_{s+b}/CL_b$ undercovers: if we set an exclusion at 95% C.L.

more than 95% of the experiments will give a number of events above the observed one for the exluded signal hypothesis s

The problem: under coverage

for low σ signals the true false exclusion rate is below 5% (when quoting according to this recipe a 95% CL exclusion)

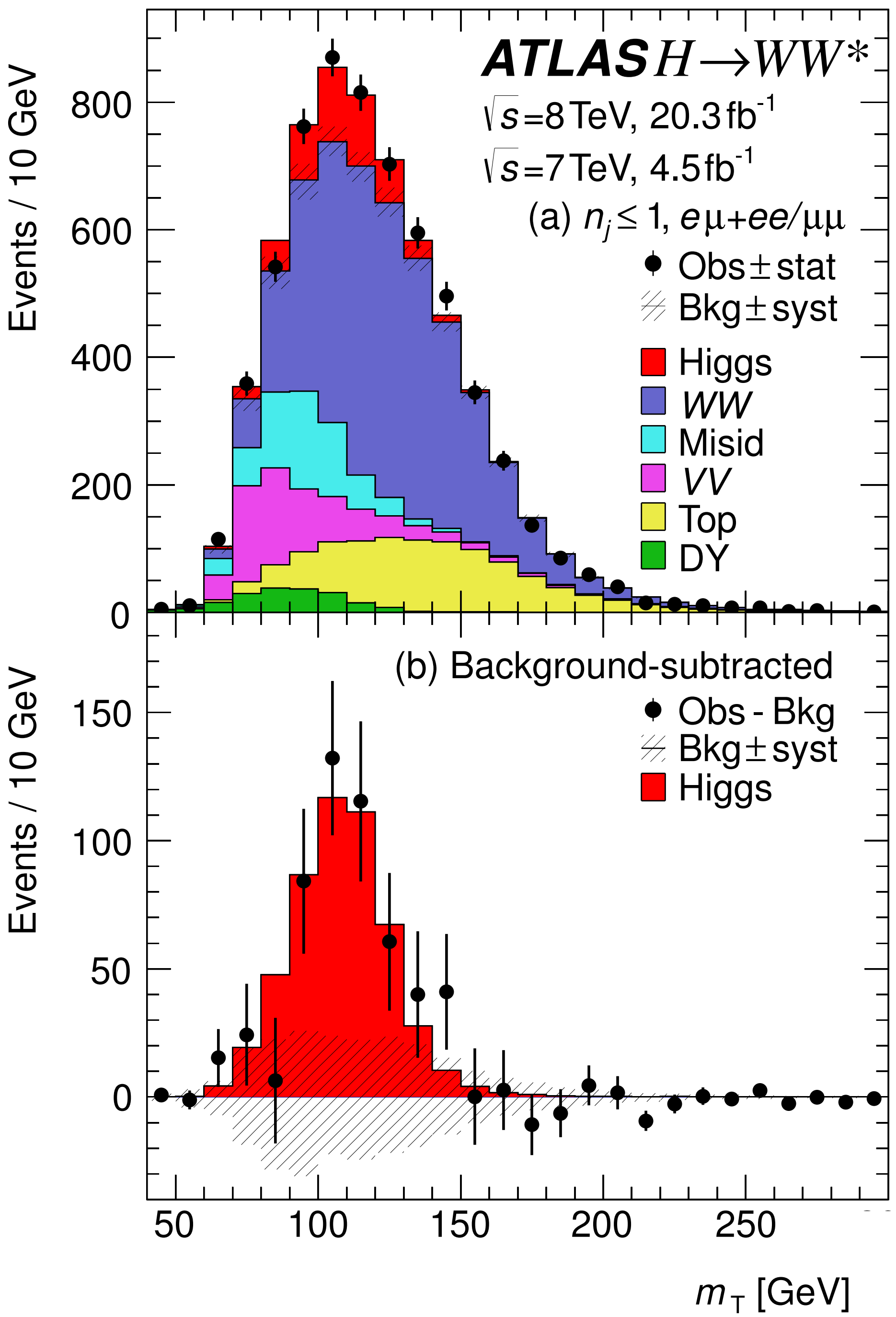


Basic Definitions

- Normally, we make **one** experiment and try to **estimate from this one experiment** the **confidence interval** at a specified CL% Confidence Level….

- In simple cases like Gaussians PDFs G(s,s_{true}) the Confidence Intrerval can be calculated analytically and ensures a complete coverage For example 68% coverage is precise for $\hat{s} \pm \sigma_{\hat{s}}$

- Typical Higgs search result is not a simple number counting experiment, but looks like this:



- Result is a distribution, not a single number
- Models for signal and background have intrinsic uncertainties

We have two hypotheses:

1. H_s there is a signal;
2. H_b there is only background

We have K bins, we know the acceptance in each bin i: ε_i^b for background, ε_i^s for signal: $\langle N_i(H_s)\rangle = \varepsilon_i^b b + \varepsilon_i^s s$

$$L(N_1,\ldots,N_K|H_s) = \prod_{i=1}^{K} Poisson(N_i, \epsilon_i^b b + \epsilon_i^s s) = \prod_{i=1}^{k} (\epsilon_i^b b + \epsilon_i^s s)^k e^{-\epsilon_i^b b - \epsilon_i^s s}$$

$$L(N_1,\ldots,N_K|H_b) = \prod_{i=1}^{K} Poisson(N_i|\epsilon_i^b) = \prod_{i=1}^{K} \frac{(\epsilon_i^b b)^{N_i}}{N_i!} e^{-\epsilon_i^b b}$$

Neyman-Pearson lemma

$$L(N_1,\ldots,N_K|H_s) = \prod_{i=1}^{K} Poisson(N_i,\epsilon_i^b b + \epsilon_i^s s) = \prod_{i=1}^{k} (\epsilon_i^b b + \epsilon_i^s s)^k e^{-\epsilon_i^b b - \epsilon_i^s s}$$

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The most powerful discriminant is the likelihood ratio

$$\lambda(N_1,\ldots,N_K|H_s,H_b) = \frac{L(N_1,\ldots,N_K|H_s)}{L(N_1,\ldots,N_K|H_b)}$$

A selection that maximises λ is such that, for a given signal efficiency ε_s, it allows to have the lowest background efficiency ε_b

Likelihood ratio for discovery

Discovery: what is the probability that the observed data are due to a background fluctuation?

Hypothesis 1: There is only background (we want to falsify this)

Hypothesis 2: There is a signal with arbitrary normalisation

If we expect **s** events from MC simulation of a signal with cross section $\boldsymbol{\sigma_s}$, we test the **s** hypothesis with an arbitrary multiplicative factor **μ** (signal strength), I.e. we test an arbitrary signal yield **μ·s.**

This means that if data are better described by a signal, we prefer it to the background hypothesis (in this sense we increase the separation power)

Assuming *b* and *s* are known without uncertainties (no systematic uncertainties)

$$\lambda(N_1, \ldots, N_K|0) = \frac{L(N_1, \ldots, N_K|b)}{L(N_1, \ldots, N_K|b + \hat{\mu}s)}$$

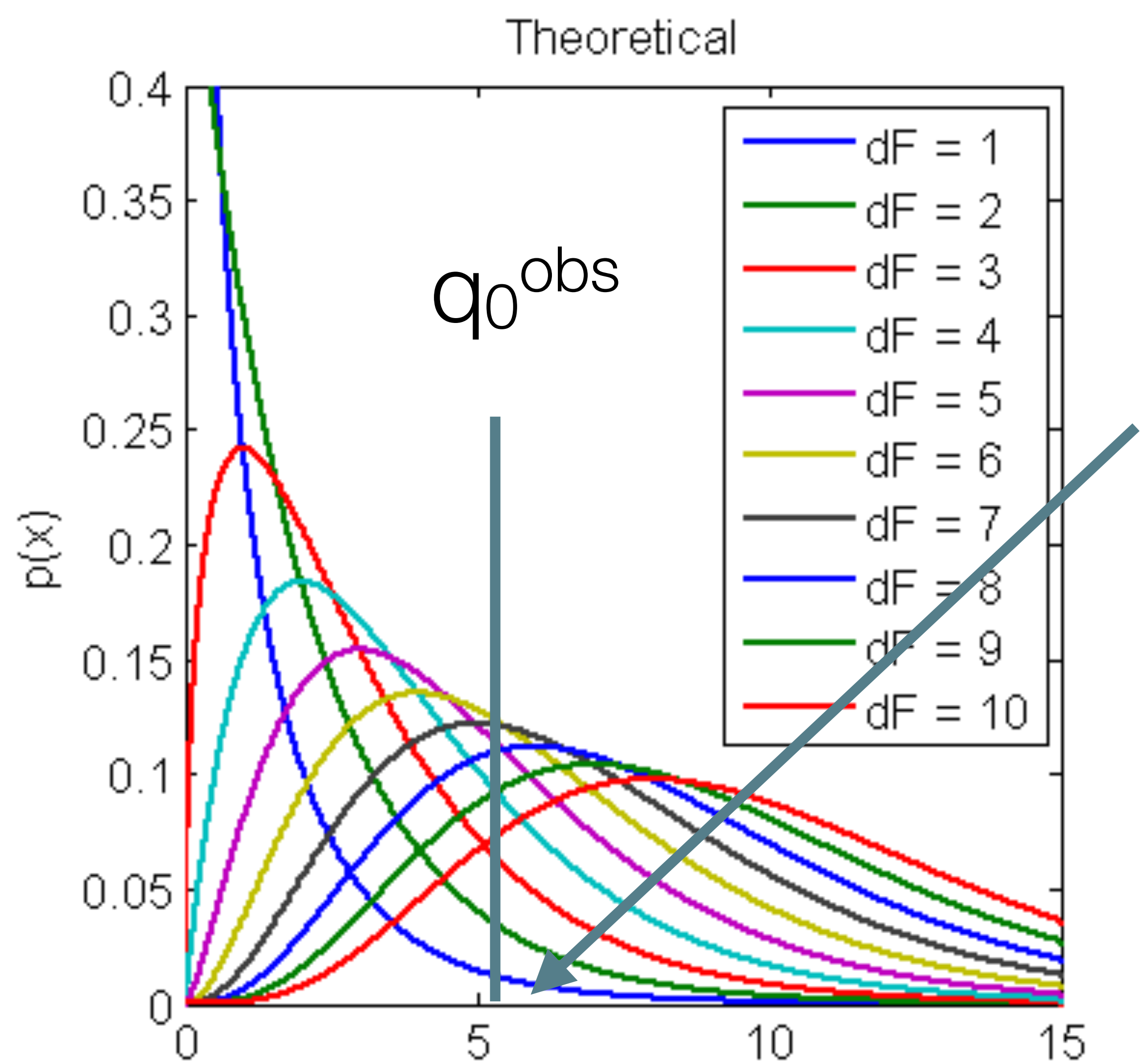
fixed number

$\hat{\mu}$ is obtained by maximising the denominator of λ

Likelihood ratio for discovery (the test statistics)

$$q_0 = -2ln\left[\frac{L(N_1,\ldots,N_K|b)}{L(N_1,\ldots,N_K|b+\hat{\mu}s)}\right]$$

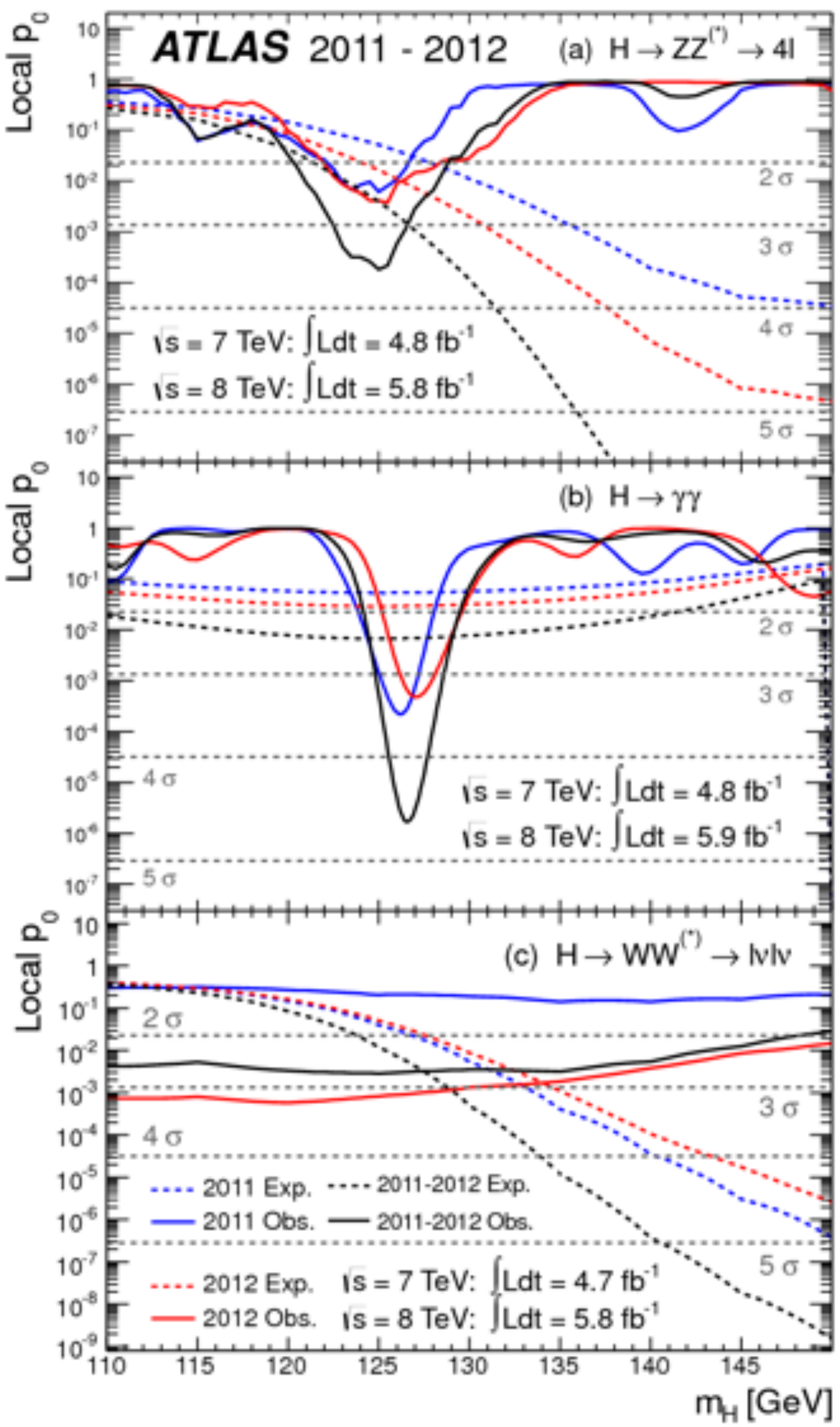
q_0 distributes according a χ^2 distribution with 1 degree of freedom (dF)



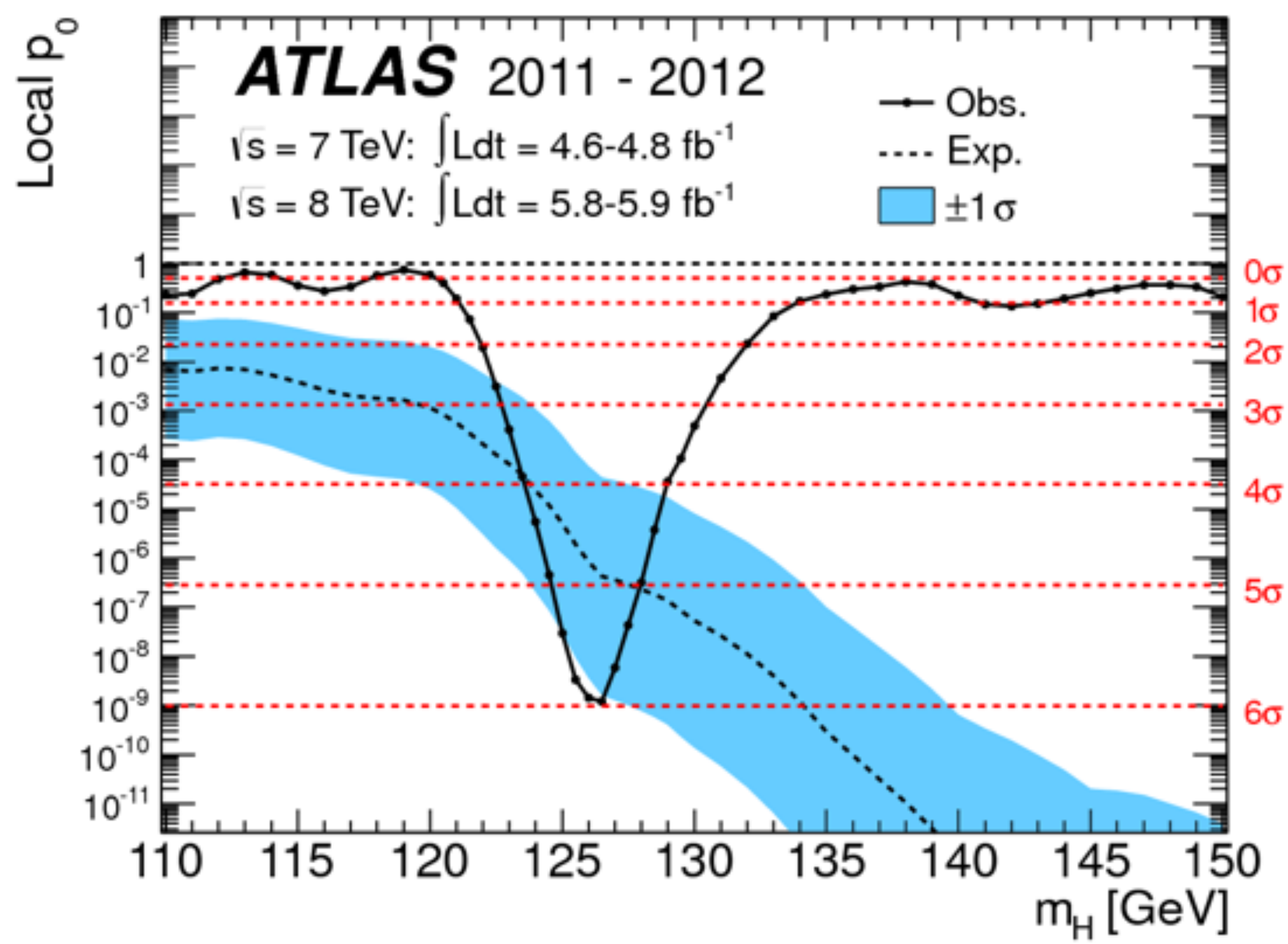
This area is the probability to have a q_0 value higher than the observed one (it is the p_0)

data are not background-like, L small, q_0 larger.

Higgs discovery



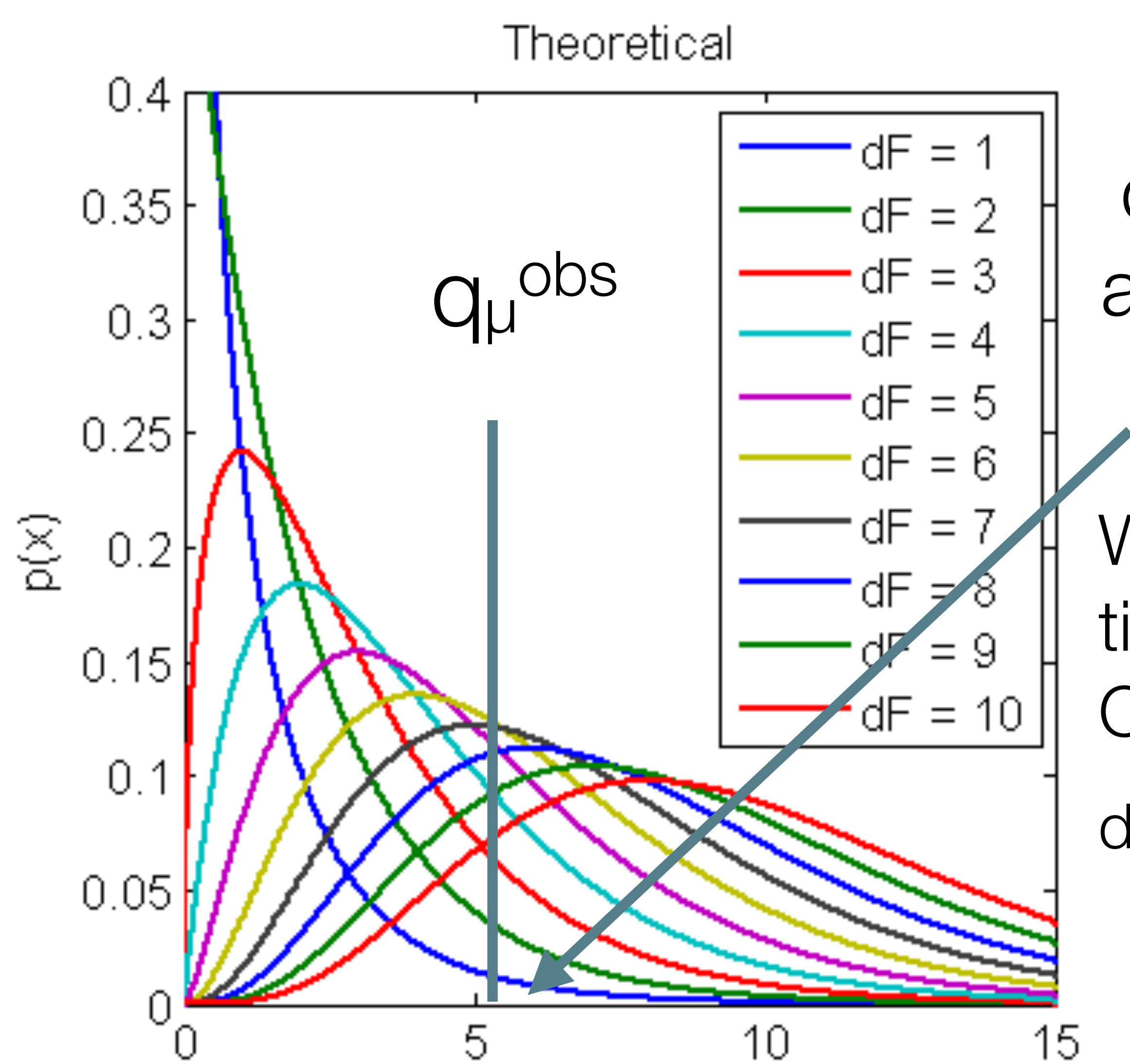
p_0 is computed for each mass hypothesis, the mass hypothesis changes the signal distributions (this plot would have no shape in case of a single count experiment)



Likelihood ratio for exclusion of signal strength μ

1) H_1 hypothesis to have a signal that is μ times the SM expectation;
2) H_μ hypothesis to have any signal with signal strength μ

$$q_\mu = -2ln\left[\frac{L(N_1,\ldots,N_K|b+\mu s)}{L(N_1,\ldots,N_K|b+\hat{\mu}s)}\right]$$



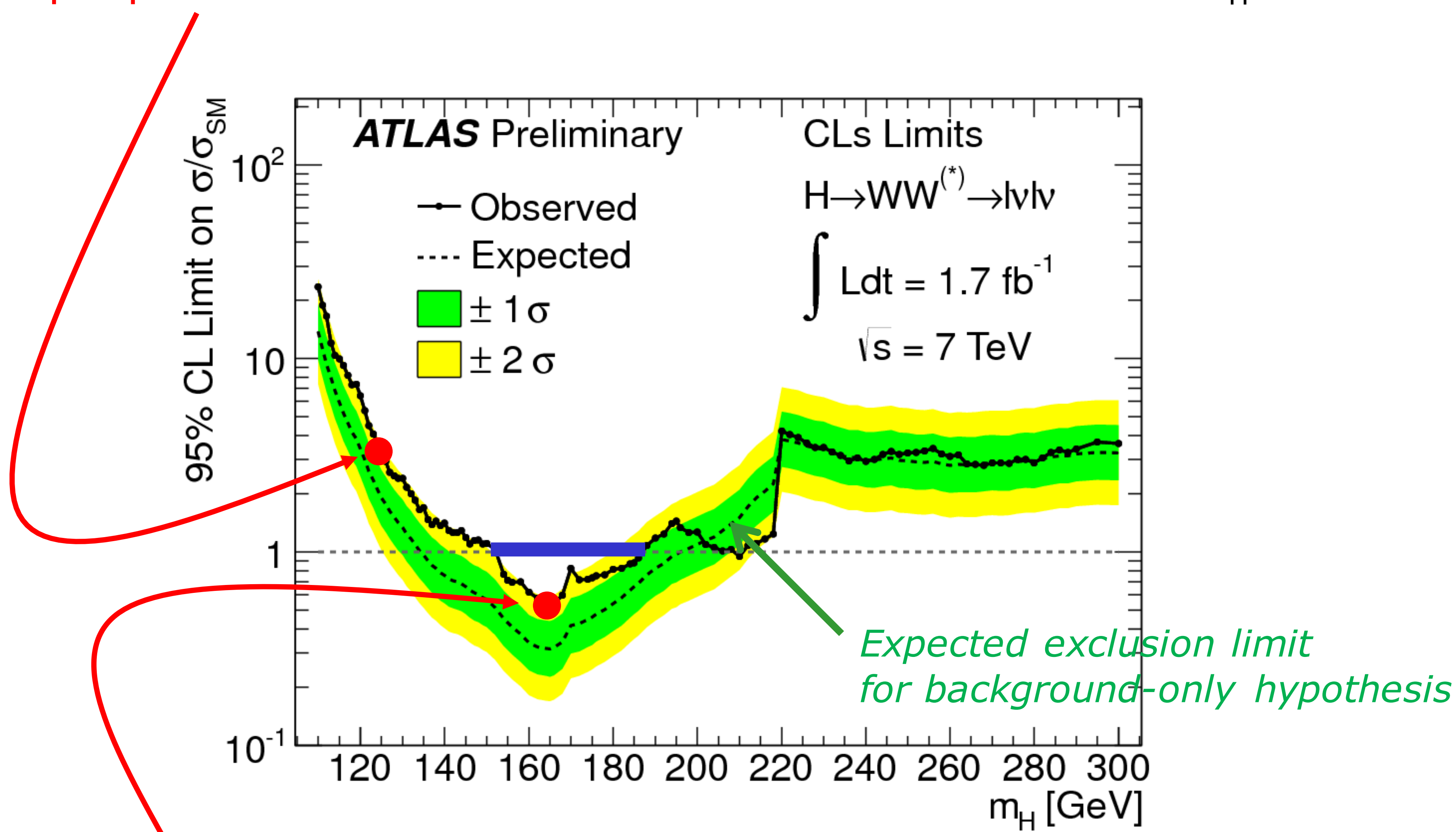
$q_\mu \geq 0$ and distributes according a χ^2 distribution with 1 degree of freedom

We say that a signal with a cross section μ times larger than the SM is excluded at 95% C.L. if $P(q_\mu > q_\mu^{obs}) < 5\%$, coverage is exact

dF: number of degree of freedom

Example – 95% Exclusion limit vs m_H for H→WW

Example point: ≈3 x SM H→WW cross-section excluded at m_H=125 GeV



Example point: ≈0.5 x SM H→WW cross-section excluded at m_H=165 GeV

Higgs with 1.0x SM cross-section excluded at 95% CL for m_H in range [150,~187]

How does likelihood ratio behaves for small signals?

Let's assume to have 1 bin:

$$q_1 = -2ln\left[\frac{L(N_1, b+s)}{L(N_1, b+\hat{\mu}s)}\right] = -2ln\left[\frac{Poisson(N_1, b+s)}{Poisson(N_1, b+\hat{\mu}s)}\right]$$

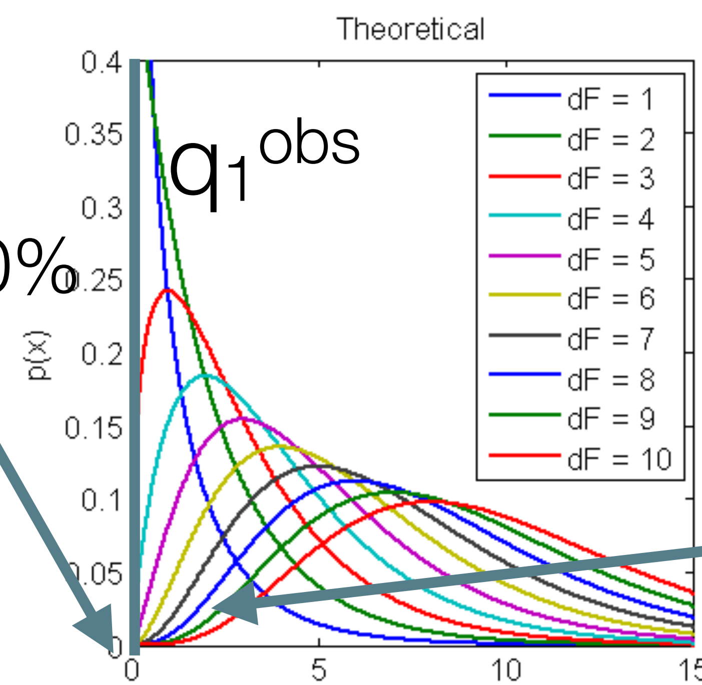
In order to evaluate $\hat{\mu}$

$$\frac{dL}{d\mu} = \frac{d}{d\mu}\frac{(b+\mu s)^{N_1}}{N_1!}e^{-b-\mu s} = \frac{s(b+\mu s)^{N_1-1}}{N_1!}e^{-b-\mu s}\left(N_1 - b - \mu s\right)$$

If data under fluctuate below b the derivative is negative, so L decreases with μ and its maximum is at $\mu = 0 \rightarrow \hat{\mu} = 0$

$$q_1 = -2ln\left[\frac{L(N_1, b+s)}{L(N_1, b)}\right]$$

CLs = 0%



100%

This term works like 1-p_b in the CL_s method, if s<<b $L(N_1,b+s)$~$L(N_1,b)$ and q_1 = 0, so we cannot exclude the signal at any confidence level.

Summary

CL_{s+b}: coverage ok, but dangerous for s<<b;
CL_s: ok, but undercoverage
Likelihood ratio: coverage ok, protected for s<<b
can be used to test distributions

Up to know, discussed only about observation and exclusions, what about measurements?

1) Who cares of measurements?

2) Measurements are useful to look for deviations from SM, tune MC, check SM prediction: i.e. sin(2β), N.P. Kobayashi-Maskawa

I measure the Higgs mass $m_{H,}$ what an error on m_H means?

Bayesian versus frequentist (the religious war)

1) the error on m_H means that there is 68% probability that the true m_H is between m_H - σ_{mH} and m_H + σ_{mH}

What this probability is? m_H has only one value… Do we mean that if we generate 100 universes in the 68% of cases m_H will lie in that interval?

Bayesian versus frequentist (the religious war)

1) the error on m_H means that there is 68% probability that the true m_H is between $m_H - \sigma_{mH}$ and $m_H + \sigma_{mH}$

~~What this probability is? m_H has only one value… Do we mean that if we generate 100 universes in the 68% of cases m_H will lie in that interval?~~

2) it is our degree of believe…, it is like a bet: What is the probability that Juventus will win the Italian league?

In this case it is subjective, and it tries to estimate an objective number:

Given the parameters I know about Juventus potentiality to win a match, if I take a sample of those parameters and try to simulate a match, what is the fraction of times Juventus will win?

There is always something subjective in this.

Frequentist approach (Neyman construction of conf. belt)

If the Higgs mass is m_H, 68% of the experiments will measure an interval $[m_H^{meas} - \sigma, m_H^{meas} + \sigma]$ that will contain the value m_H.

There is no subjective statement, the probability has a strictly frequentist definition

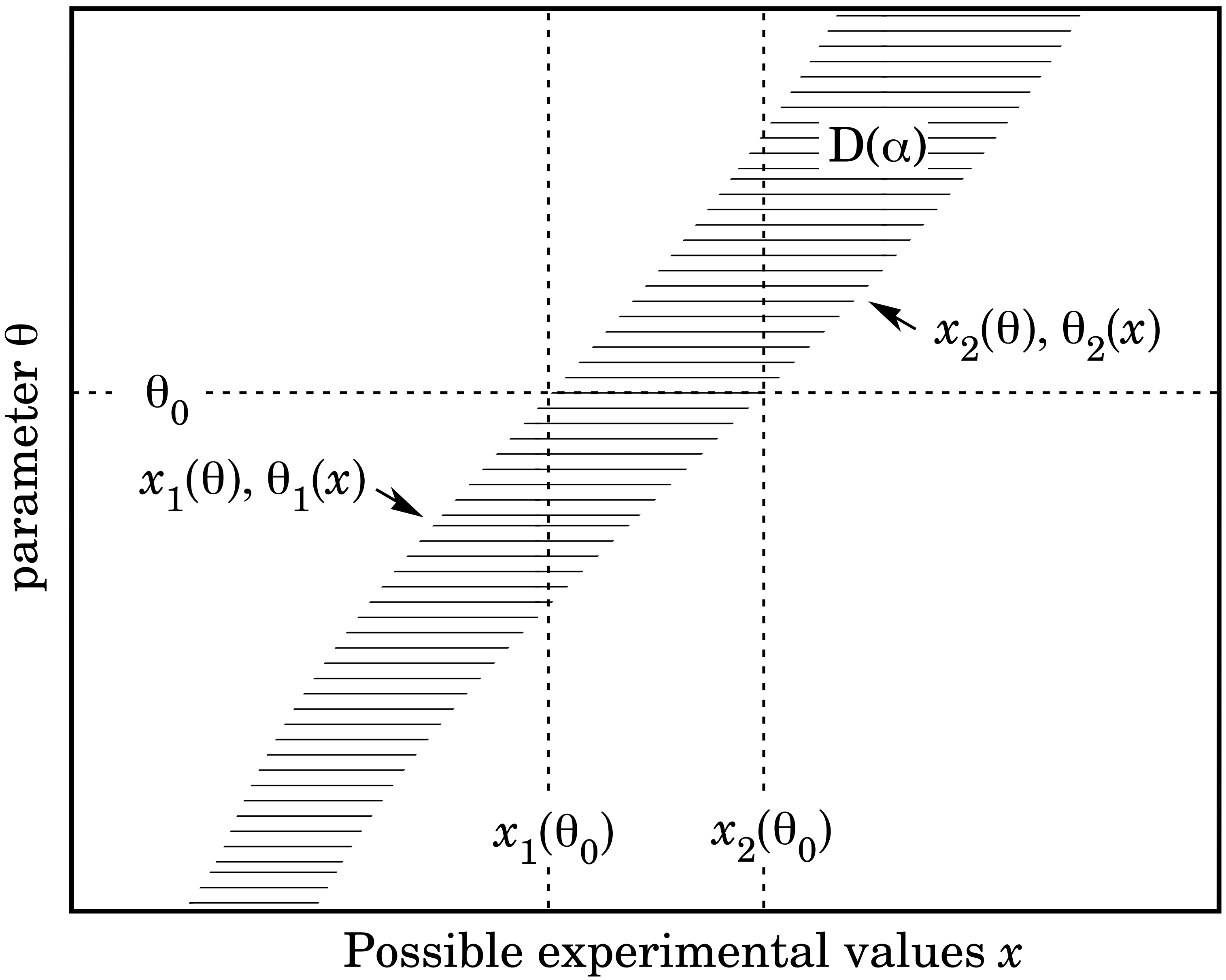
Neyman construction of confidence belt:

$f(x;\theta)$ distribution of x given θ

$$P(x_1 < x < x_2; \theta) = \int_{x_1}^{x_2} f(x;\theta)\, dx \geq 1 - \alpha$$

for 1σ $1-\alpha=0.68$

when we change θ we get two curves for x_1 and x_2. We build the confidence belt using simulation.



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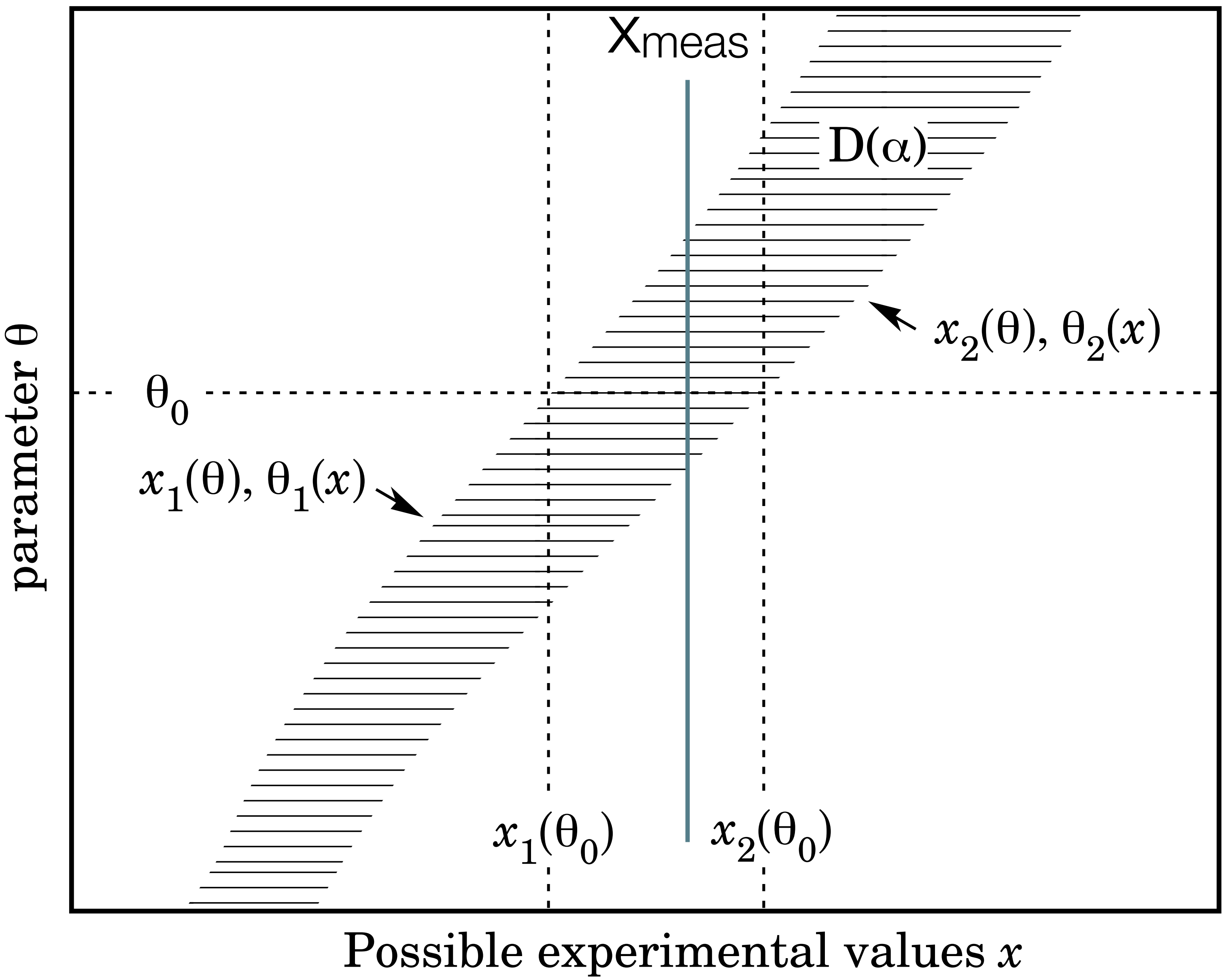
Then we measure x_{meas}



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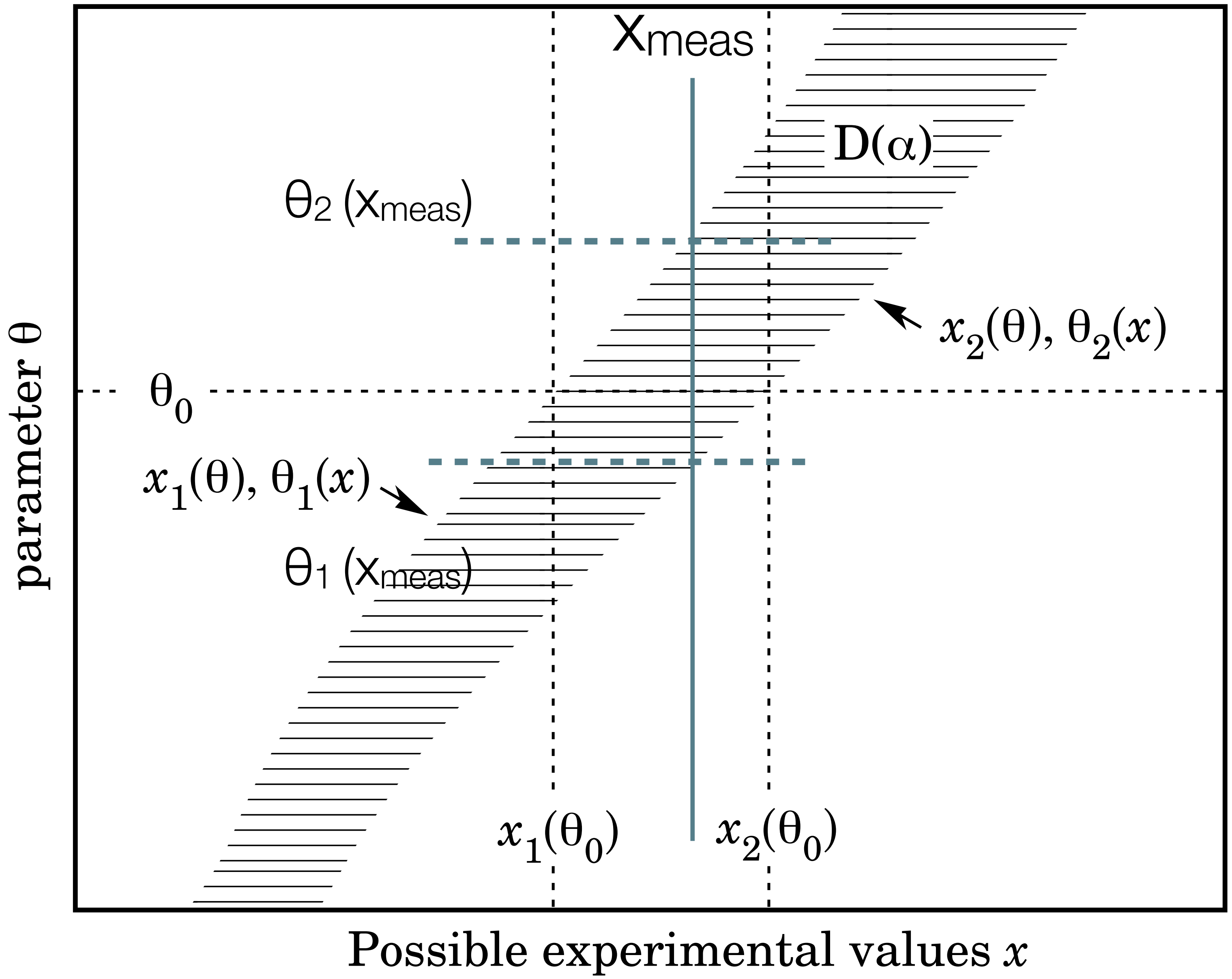
for 1σ $1-\alpha=0.68$

when we change θ we get two curves for x_1 and x_2. We build the confidence belt using simulation.

then we measure x_{meas}

we set as interval for θ the range $[\theta_1, \theta_2]$.

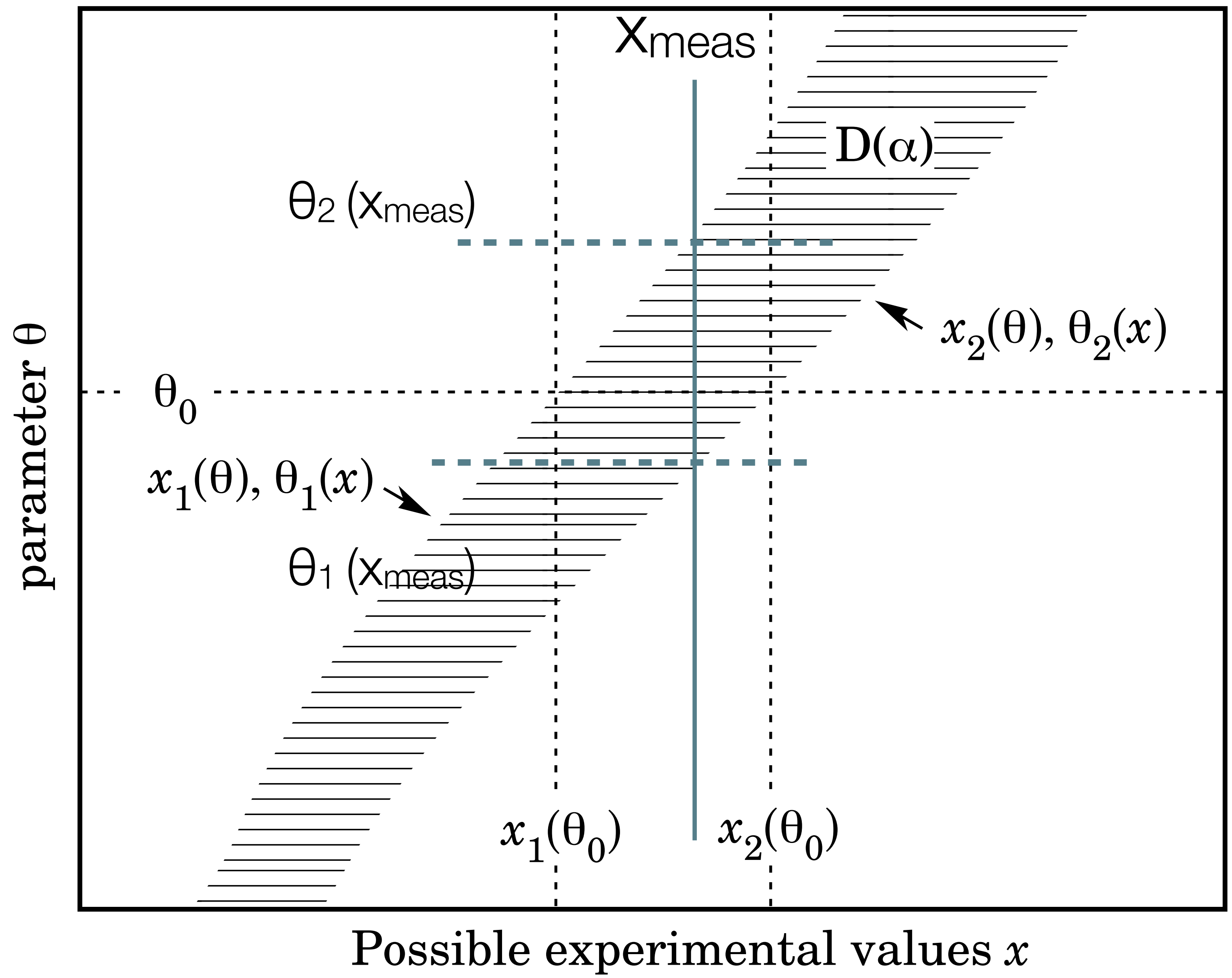


Frequentist approach (Neyman constr. of conf. belt)

If the Higgs mass is m_H, 68% of the experiments will measure an interval $[m_H^{low}, m_H^{high}]$ that will contain the value m_H.

There is no subjective statement, the probability has a strictly frequentist definition

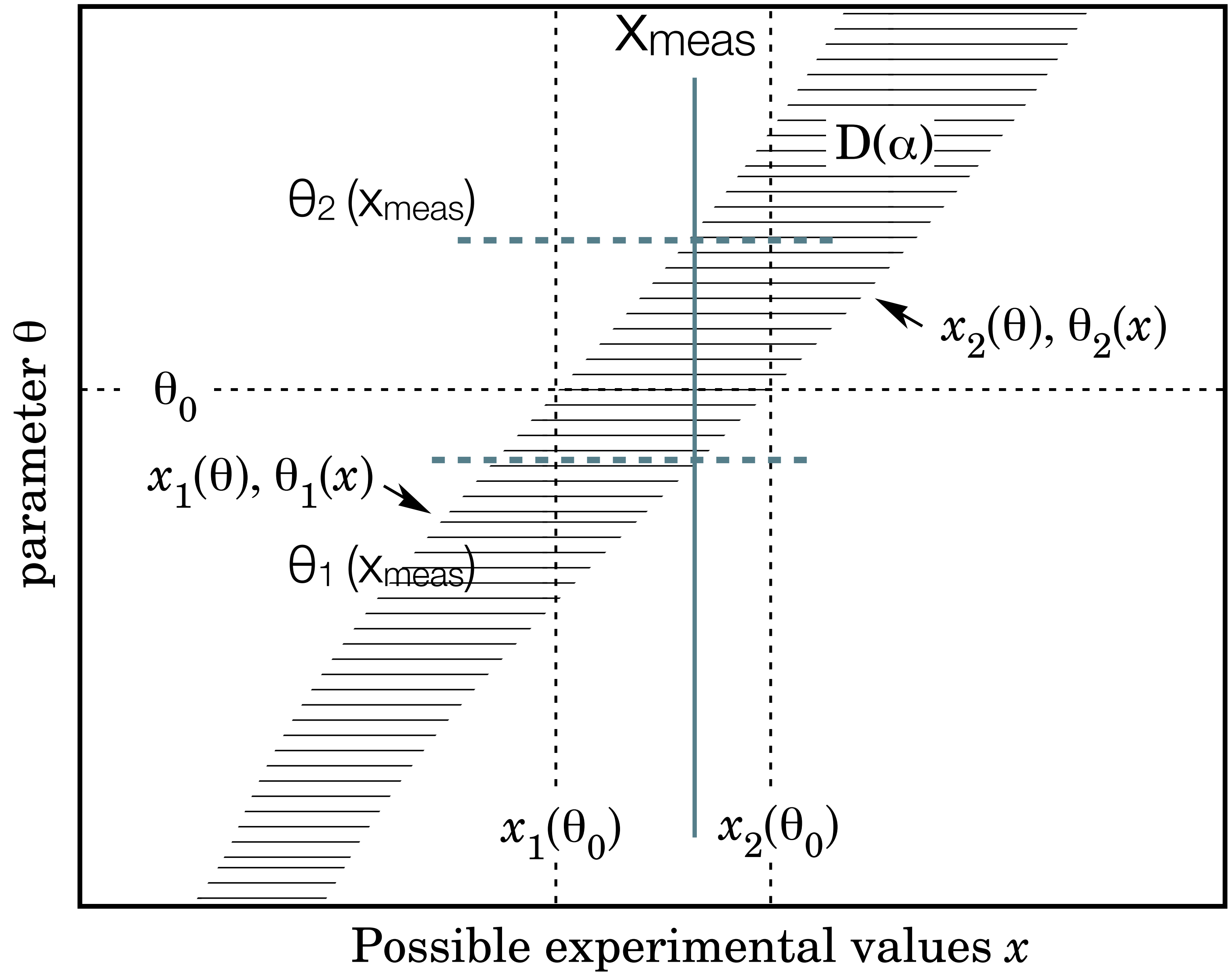
if θ_0 is the true value, we will have $x_1 < x_{meas} < x_2$ in 1-α of the cases (experiments) and consequently $\theta_1 < \theta_0 < \theta_2$ in the same fraction of cases, where θ_1 and θ_2 are random variables that is the outcome of the experiment.



Frequentist approach (Neyman constr. of conf. belt)

$$P(x_1 < x < x_2; \theta) = \int_{x_1}^{x_2} f(x;\theta)\, dx \geq 1 - \alpha$$

it is not enough to define x_1 and x_2, need to add further informations: i.e. central values x_c is such that $P(x < x_1) = P(x > x_2) = \alpha/2$



The Bayesian Way

likelihood of measured x given θ

new distribution for θ, improved after the measurement of x

a-priori distribution for θ

$$p(\theta \mid x) = \frac{L(x \mid \theta)\pi(\theta)}{\int L(x \mid \theta)\pi(\theta)d\theta}$$

if θ and x are random variables, this is a theorem otherwise it is the definition of $p(\theta, x)$

- Can the model have a probability?
- We assign a degree of belief in models parameterized by θ
- Instead of talking about confidence intervals we talk about credible intervals, where p(θ|x) is the credibility of θ given the data.

Nuisance Parameters (Systematics)

- Nuisance – a thing causing inconvenience or annoyance (Oxford Dictionary)
- Systematic Errors are equivalent in the statisticians jargon to Nuisance parameters – parameters of no interest…
  Will the Physicist ever get used to this jargon?
- D. Sinervo classified uncertainties into three classes classes:
  - **Class I**: Statistics like – uncertainties that are reduced with increasing statistics. Example: Calibration constants for a detector whose precision of (auxiliary) measurement is statistics limited
  - **Class II**: Systematic uncertainties that arise from one's limited knowledge of some data features and cannot be constrained by auxiliary measurements … One has to do some assumptions. Example: Background uncertainties due to fakes, isolation criteria in QCD events, shape uncertainties…. These uncertainties do not normally scale down with increasing statistics
  - **Class III**: The "Bayesian" kind… The theoretically motivated ones… Uncertainties in the model, Parton Distribution Functions, Hadronization Models…..

Nuisance Parameters (Systematics)

- There are two related issues:
  - Classifying and estimating the systematic uncertainties
  - Implementing them in the analysis
- The physicist must make the difference between cross checks and identifying the sources of the systematic uncertainty.
  - Shifting cuts around and measure the effect on the observable… Very often the observed variation is dominated by the statistical uncertainty in the measurement.

Treatment of Systematic Errors , the Bayesian Way

- Marginalization (Integrating) (The C&H Hybrid)
  - Integrate L over possible values of nuisance parameters (weighted by their prior belief functions -- Gaussian,gamma, others...)
  - Consistent Bayesian interpretation of uncertainty on nuisance parameters

- Note that in that sense MC “statistical” uncertainties (like background statistical uncertainty) are systematic uncertainties

Integrating Out The Nuisance Parameters (Marginalization)

$$p(\theta,\lambda \mid x) = \frac{L(x \mid \theta,\lambda)\pi(\theta,\lambda)}{\int L(x \mid \theta,\lambda)\pi(\theta,\lambda)d\theta d\lambda} = \frac{L(x \mid \theta,\lambda)\pi(\theta,\lambda)}{Normalization}$$

- Our degree of belief in θ is the sum of our degree of belief in θ given λ (nuisance parameter), over "all" possible values of λ

$$p(\theta \mid x) = \int p(\theta,\lambda \mid x)d\lambda$$

Priors

$$P(\theta \mid data) \sim \int L(data \mid \theta, \lambda)\pi(\lambda) d\theta d\lambda$$

- A prior probability is interpreted as a description of what we believe about a parameter preceding the current experiment
  - **Informative Priors**: When you have some information about λ the prior might be informative (Gaussian or Truncated Gaussians…)
    - Most would say that subjective informative priors about the parameters of interest should be avoided ("….what's wrong with assuming that there is a Higgs in the mass range [115,140] with equal probability for each mass point?")
    - Subjective informative priors about the Nuisance parameters are more difficult to argue with
      - These Priors can come from our assumed model (Pythia, Herwig etc…)
      - These priors can come from subsidiary measurements of the response of the detector to the photon energy, for example.
      - Some priors come from subjective assumptions (theoretical, prejudice symmetries….) of our model

Priors – Uninformative Priors

- **Uninformative Priors**: All priors on the parameter of interest should be uninformative….
  IS THAT SO?
  Therefore flat uninformative priors are most common in HEP.
  - When taking a uniform prior for the Higgs mass [115, ∞]… is it really uninformative? do uninformative priors exist?
  - When constructing an uninformative prior you actually put some information in it…

- **But** a prior flat in the coupling *g* will not be flat in $\sigma \sim g^2$
  Depends on the metric!
  (→ try Jeffrey Priors)
- Moreover, flat priors are improper and lead to serious problems of undercoverage (when one deals with >1 channel, i.e. beyond counting, one should AVOID them

–See Joel Heinrich Phystat 2005

Choice of Priors

- A.W.F. Edwards: "Let me say at once that I can see no reason why it should always be possible to eliminate nuisance parameters. Indeed, one of the many objections to Bayesian inference is that is always permits this elimination."

  Anonymous: "Who the ---- is A.W.F. Edwards…" http://en.wikipedia.org/wiki/A._W._F._Edwards

- But can you really argue with subjective informative priors about the Nuisance parameters
  (results of analysis are aimed at the broad scientific community.. See talk by Leszek Roszkowski constrained MSSM)

- Choosing the right priors is a science by itself

- Should we publish Bayesian (or hybrid) results with various priors?
- Should we investigate the coverage of Bayesian (credible) intervals?

- Anyway, results should be given with the priors specified

C&H Hybrid Method

- This method is coping with the Nuisance parameters by averaging on them weighted by a posterior.
- The Bayesian nature of the calculation is in the Nuisance parameters only….
- Say in a subsidiary measurement y of b, then the posterior is *p(b|y);* μ is the *x* expectation.
- C&H will calculate the p-value of the observation (x_o, y_o)

$$p(x_o, y_o \mid \mu) = \int_0^\infty p(x_o \mid y_o, \mu) p(b \mid y_o) db$$

$$p(b \mid y_o) = \frac{p(y_o \mid b) p(b)}{p(y_o)}$$

$$p(y_o \mid b) = G(y_o \mid b, \sigma_b)$$

$$p(b) \ \ uniform$$

Note:
The original C&H used the Luminosity as the Nuisance parameter….

The Profile Likelihood Method

$$\ell(s) = \frac{L(s,\hat{\hat{b}})}{L(\hat{s},\hat{b})} \Rightarrow Q(s) = \frac{L(s,\hat{\hat{b}})}{L(\hat{s},\hat{b})} \qquad -2\ln Q(s) = -2\ln\frac{L(s,\hat{\hat{b}})}{L(\hat{s},\hat{b})} \to \chi^2(s)$$

$$\Delta\chi^2 = 2.7 \to 90\%\ C.I.$$

- The advantages of the Profile Likelihood
  - It has been with us for years….. (MINOS of MINUIT) (**Fred James**)
  - In the asymptotic limit it is approaching a χ^2 distribution

F. James, e.g. Computer Phys. Comm. 20 (1980) 29 -35
W. Rolke, A. Lopez, J.Conrad. Nucl. Inst.Meth A 551 (2005) 493-503

The Profile Likelihood for Significance Calculation

- A counting experiment with background uncertainty

$$L(n, b_{meas} \mid \mu, s, b) = Poiss(n \mid \mu s + b) G(b_{meas} \mid b, \sigma_b)$$

- The Likelihood-ratio

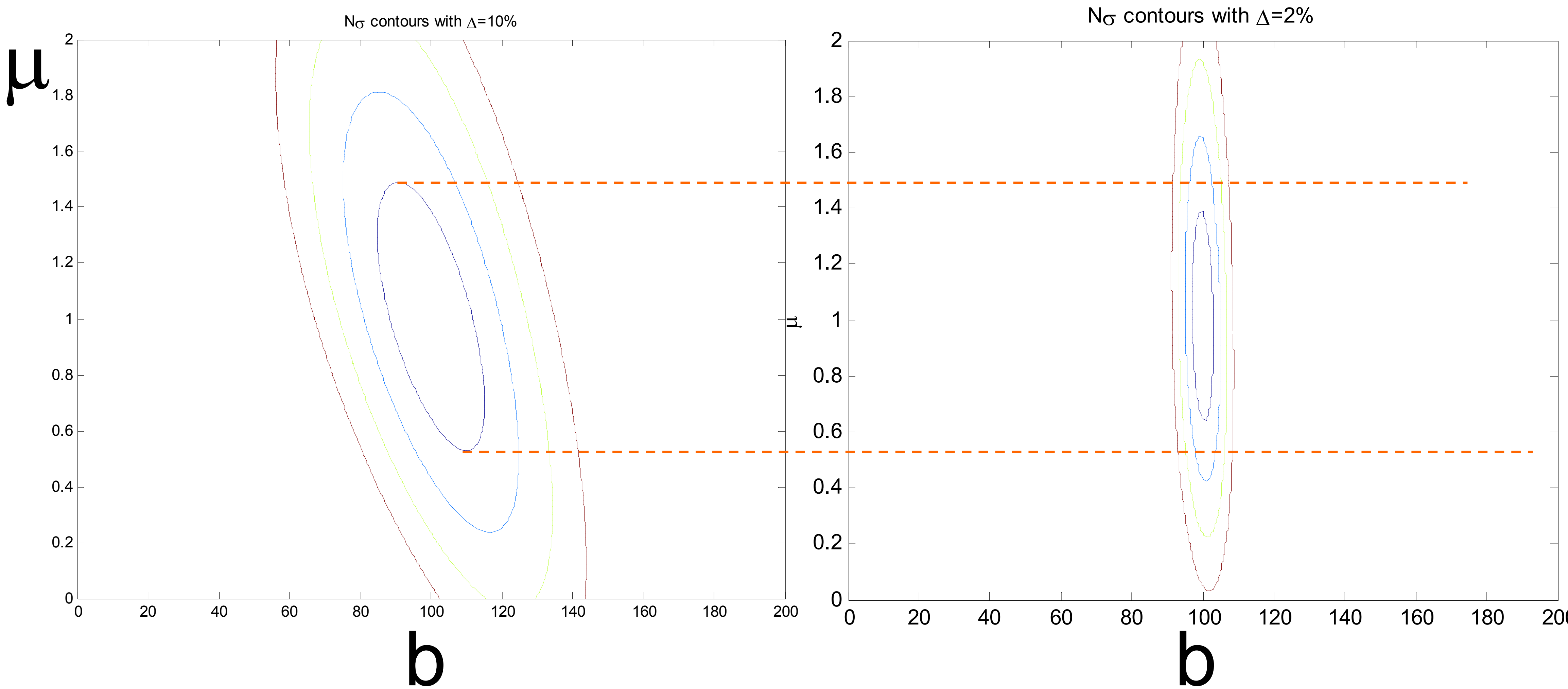
$$\lambda(\mu, b) = \frac{L(n, b_{meas} \mid \mu, s, b)}{L(n, b_{meas} \mid \hat{\mu}, s, \hat{b})}$$

Where $\hat{s}, \hat{b}$ are MLE

$-2\log\lambda(\mu)$ is distributed as a χ^2 with N degrees of freedom , N being the number of free parameters (parameters of interest)

(in this case N=2)

Confidence intervals



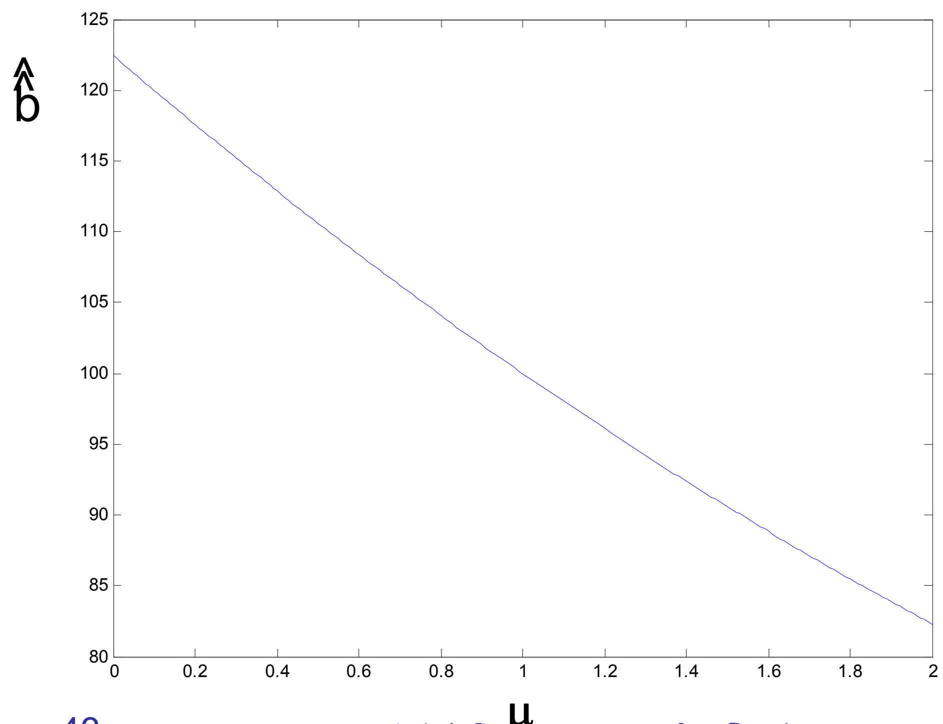
For N_{obs}=150 , b_{meas} =100 , s=50

Profiling the Likelihood

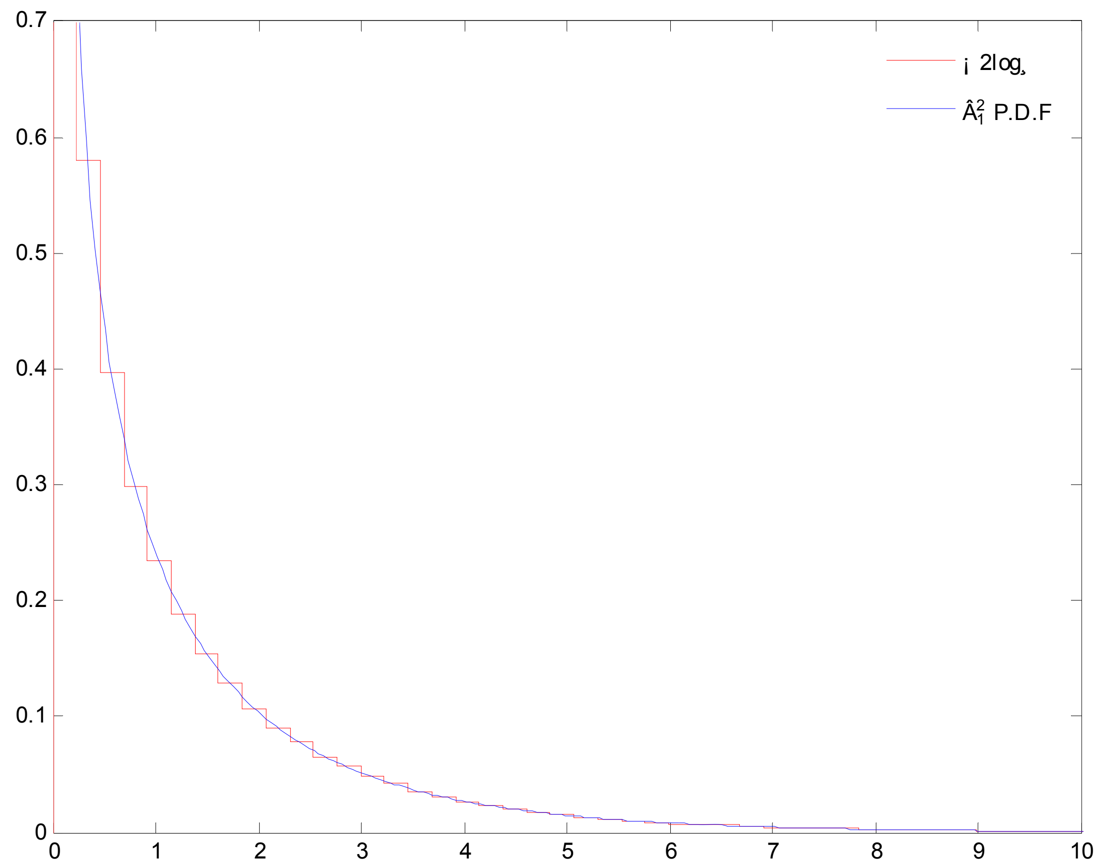
- Profile Likelihood:

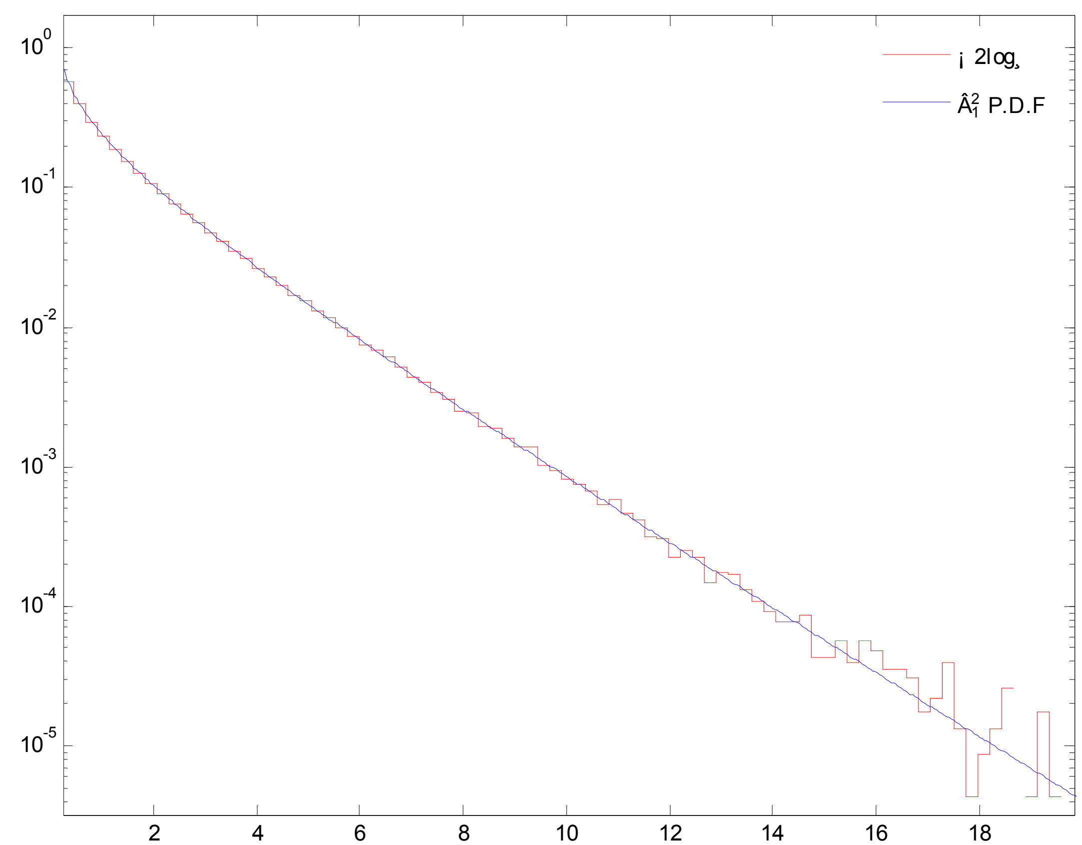
μ

$$\hat{\hat{b}}(\mu) = \frac{1}{2}\left\{ b_{meas} - \mu s - \sigma_b^2 + \sqrt{(b_{meas} + \mu s - \sigma_b^2)^2 + 4n\sigma_b^2} \right\}$$



- distributes as a χ^2 with 1 d.o.f
- This ensures simplicity, coverage, speed





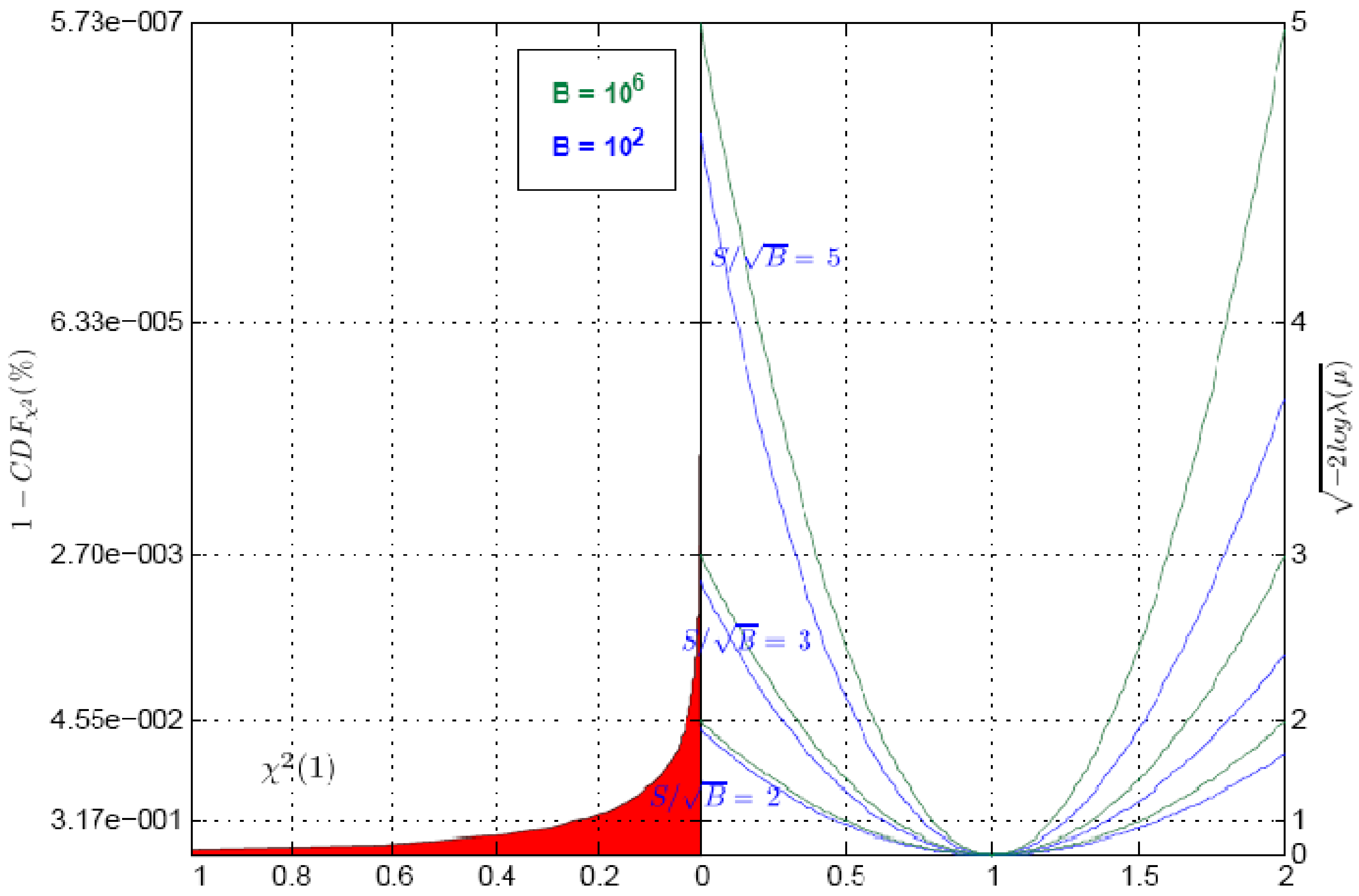
The Profile Likelihood for Significance Calculation

$$-2\log\lambda(\hat{\mu} \pm N\sigma_{\hat{\mu}}) = N^2$$

$$N = \sqrt{-2\log\lambda(\mu)}$$

- In particular if we generate background only experiments, $\lambda(\mu=0)$ is distributed as χ^2 with 1 d.o.f
- Discovery has to do with a low probability of the background only experiment to fluctuate and give us a signal like result….
- To estimate a discovery sensitivity we simulate a data compatible with a signal (s+b) and evaluate for this data $\lambda(\mu=0)$. For this data, the MLE of μ is 1

0% BG Systematics



A Lesson in Systematic

- In absence of systematics significance can be approximated to be $\frac{s}{\sqrt{b}}$

- However if there is systematics, say, Δb the significance is reduced to

$$\frac{s}{\sqrt{\left(\sqrt{b}\right)^2 + (\Delta \cdot b)^2}} = \frac{s}{\sqrt{b(1+\Delta^2 \cdot b)}} \to \frac{s}{\Delta \cdot b}$$

- For 5σ one needs

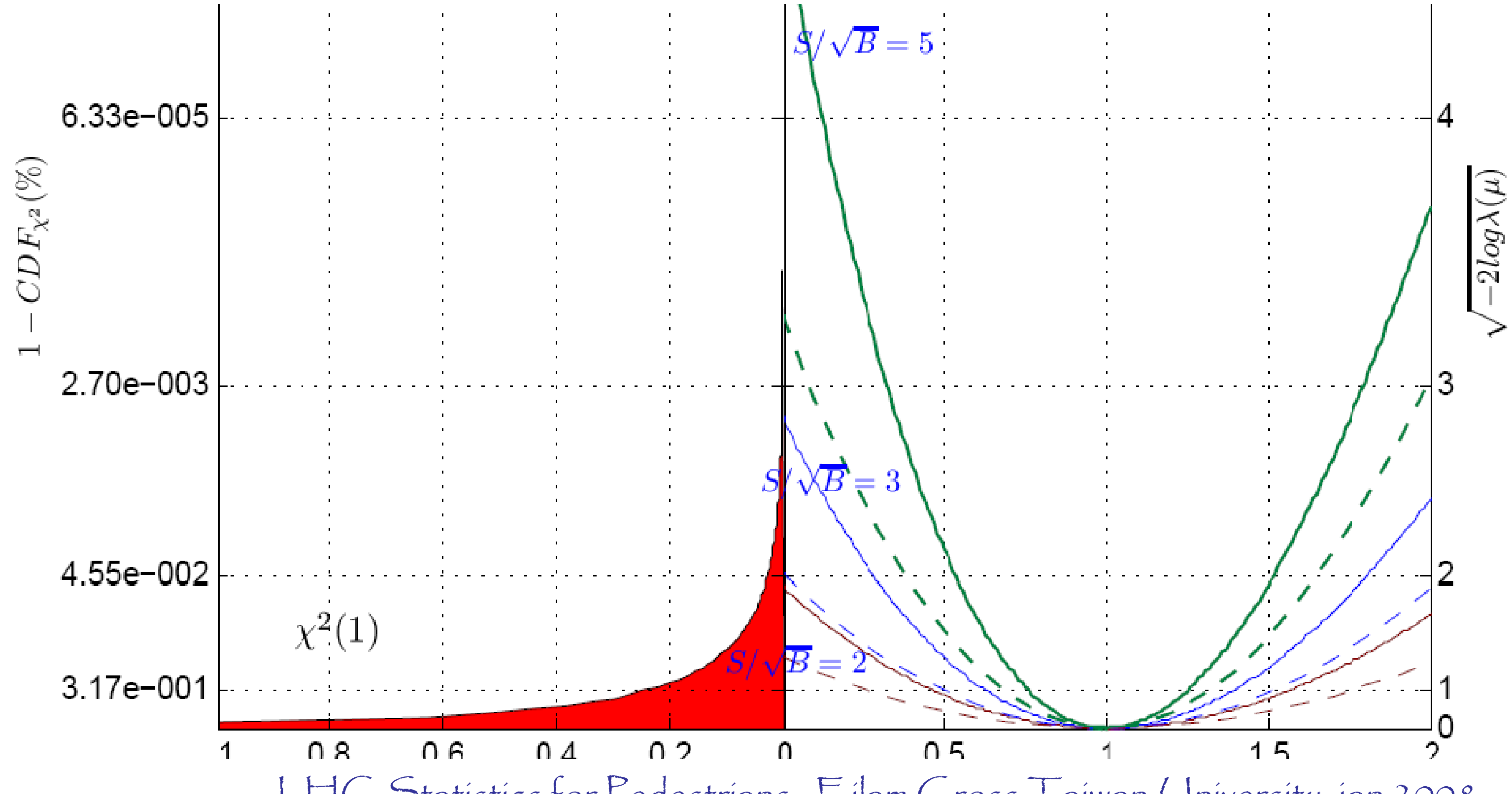
$$\frac{s}{b} > 5\Delta$$

- For 10% systematics this implies

$$\frac{s}{b} > 0.5$$

With 10% Background Systematics

For b=100 with 10% systematics, significance for S/√B=5 drops to ~3.6



Profile Likelihood

- The speed and ease allow us to produce all sorts of views in seconds!
- No numerical problems, can go up to any significance

Why Profile Likelihood?

- For SUSY interpretations you usually have results in a grid (i.e. tgβ,m_A)
- Each point is a different experiment
- There are 10s-100000s of possible points per channel
- In a shape-based analysis each bin is treated like a channel….
- The difference between O(minutes) per point and O(0.1 seconds) per point is critical!

Exclusion with Profile Likelihood

- Exclusion is related to the probability of the "would be" signal to fluctuate down to the background only region (i.e. the p-value of the s+b "observation")

- Here we suppose the data is the background only and the exclusion sensitivity is given by

$$N = \sqrt{-2\lambda(\mu = 1)}$$

- Exclusion at the 95% C.L. means N=2

Signal Efficiencies Uncertainties

$$L(\mu\varepsilon s + b)$$

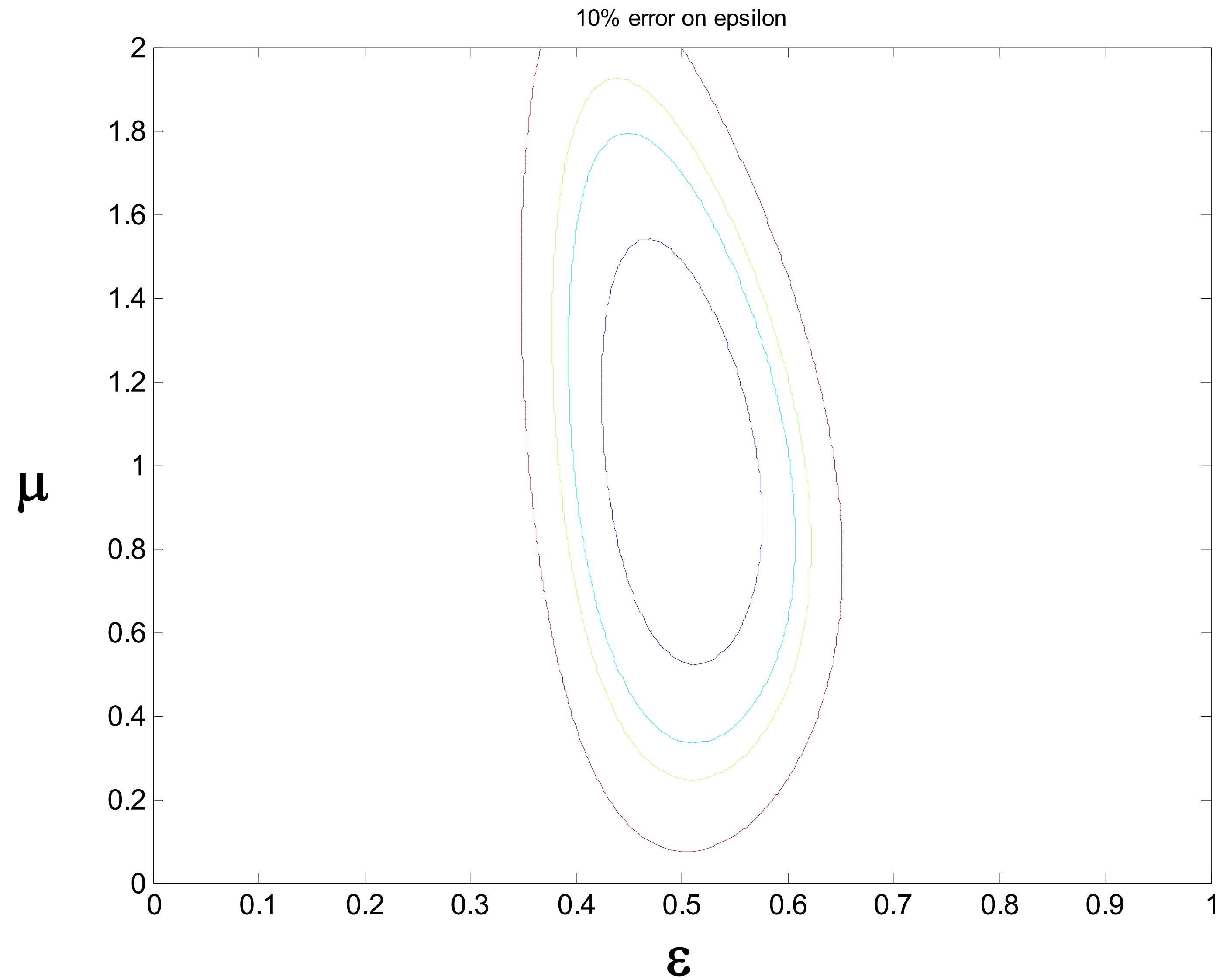
- How to cope with
  with background and efficiency systematics

- Efficiency systematics have no effect on discovery sensitivity but can have large effects on exclusion sensitivity

Including error on signal efficiency

$$L(\mu) = Poiss(n \mid \mu\varepsilon s + b)G(b_{meas} \mid b)G(\varepsilon_{meas} \mid \varepsilon)$$

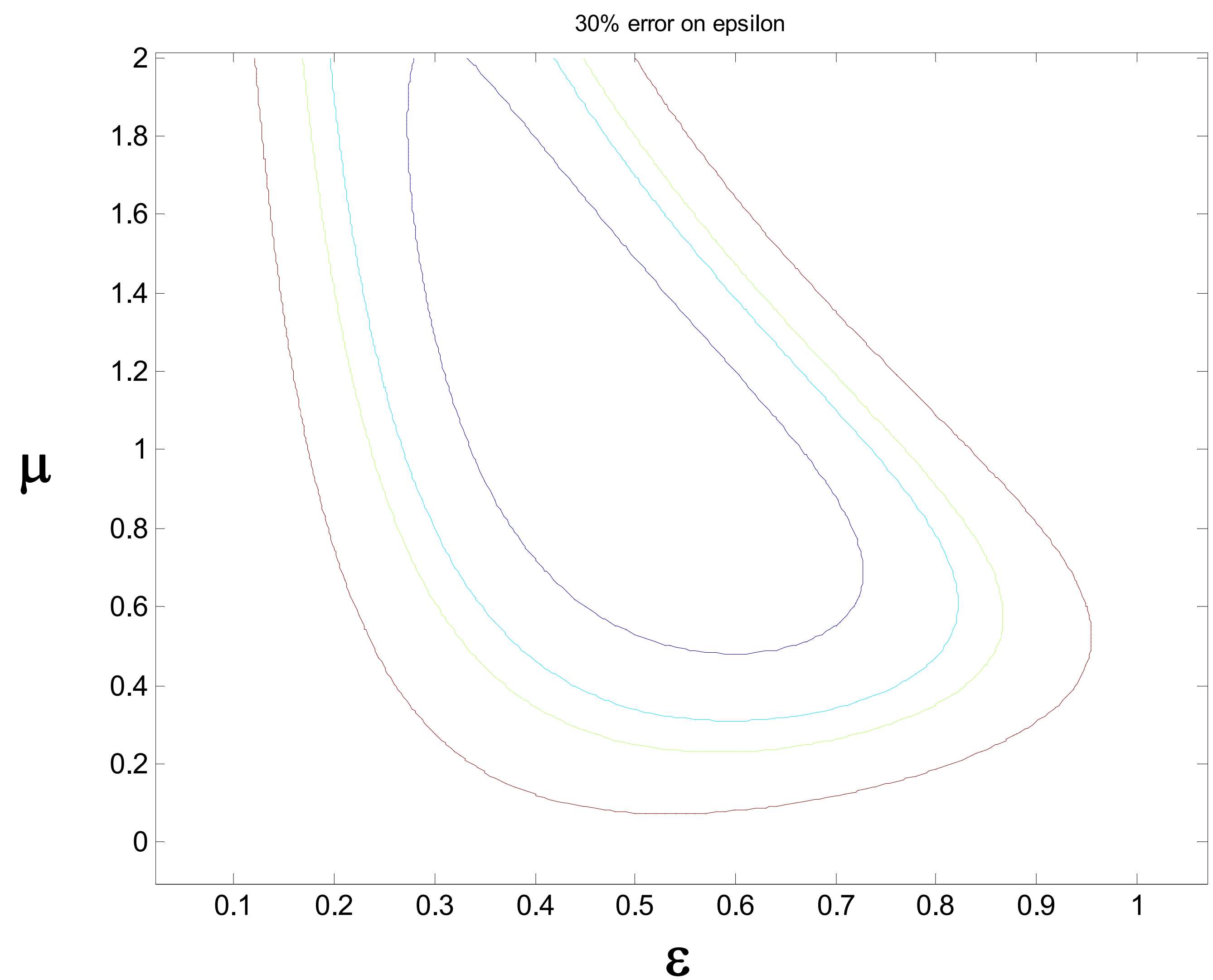
$-2\log\lambda(\mu,\varepsilon)$



Including error on signal efficiency

$$L(\mu) = Poiss(n \mid \mu\varepsilon s + b)G(b_{meas} \mid b)G(\varepsilon_{meas} \mid \varepsilon)$$

$$-2\log\lambda(\mu,\varepsilon)$$



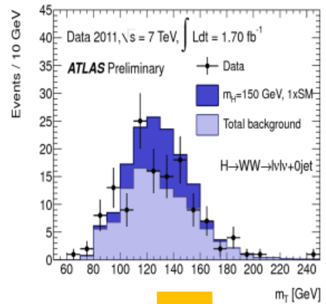
Conclusions

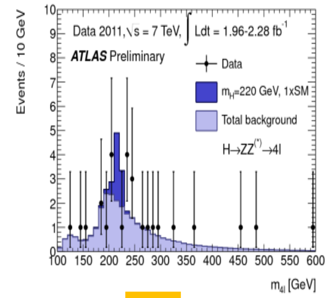
Pros and Cons Profile Likelihood

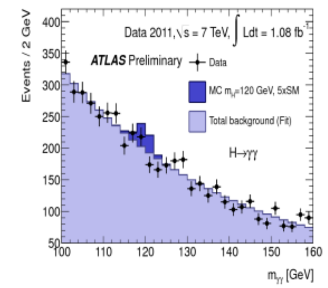
- CONS:
  - The only disadvantage I see is its incapability to take the Look Elsewhere Effect in a built-in way….
  - One has to take the Look Elsewhere Effect in the LEP way (Using MC and factorize the resulting significance- need to be studied)
- PROS:
  - It is simple and easy to understand and apply
  - It is statistically reliable and a frequentists favorite
  - It can cope with Systematics and has the proper coverage
  - It is FAST!!!!!! O(0.1 Sec) vs O(Minutes).
  - Its probably the only method that can cope with as many as SUSY scenarios one wants!

Combining Higgs channels (and experiments)

- Procedure: define joint likelihood







$$L(\mu,\theta_{comb}) = L_{H\to WW}(\mu,\theta_{WW})\cdot L_{H\to ZZ}(\mu,\theta_{ZZ})\cdot L_{H\to\gamma\gamma}(\mu,\theta_{\gamma\gamma})\cdot\ldots$$

$$L(\mu,\theta_{LHC}) = L_{ATLAS}(\mu,\theta_{ATLAS})\cdot L_{CMS}(\mu,\theta_{CMS})\cdot\ldots$$

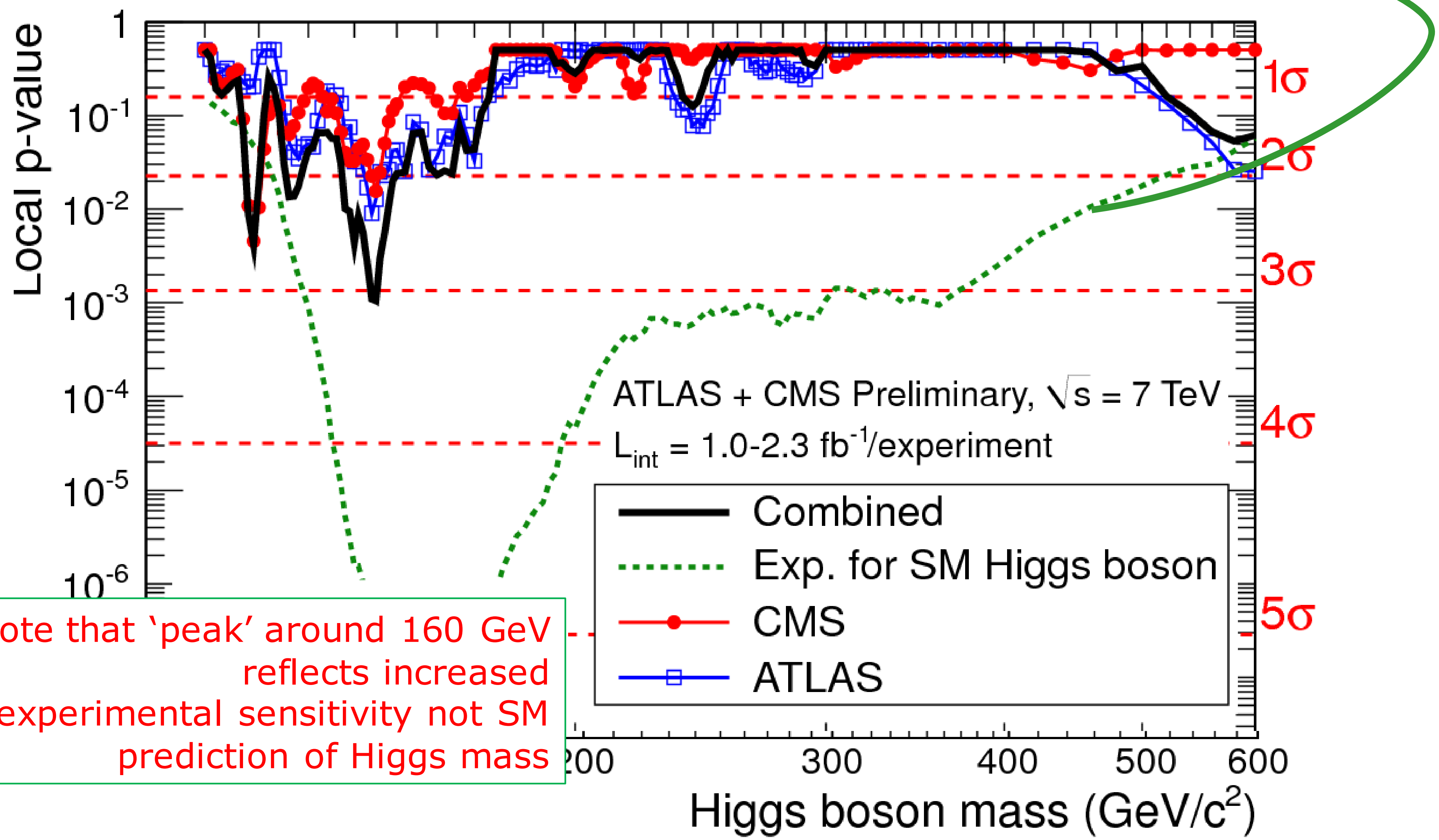
- Correlations between θ_{WW},$\theta_{\gamma\gamma}$ etc and between θ_{ATLAS},θ_{CMS} requires careful consideration!
- The construction profile likelihood ratio test statistic from joint likelihood and proceed as usual

$$\tilde{q}_\mu = -2\ln\frac{L(data\,|\,\mu,\hat{\hat{\theta}}_\mu)}{L(data\,|\,\hat{\mu},\hat{\theta})}$$

Wouter Verkerke, NIKHEF

Comb: p-value of background-only hypothesis (‘discovery’)

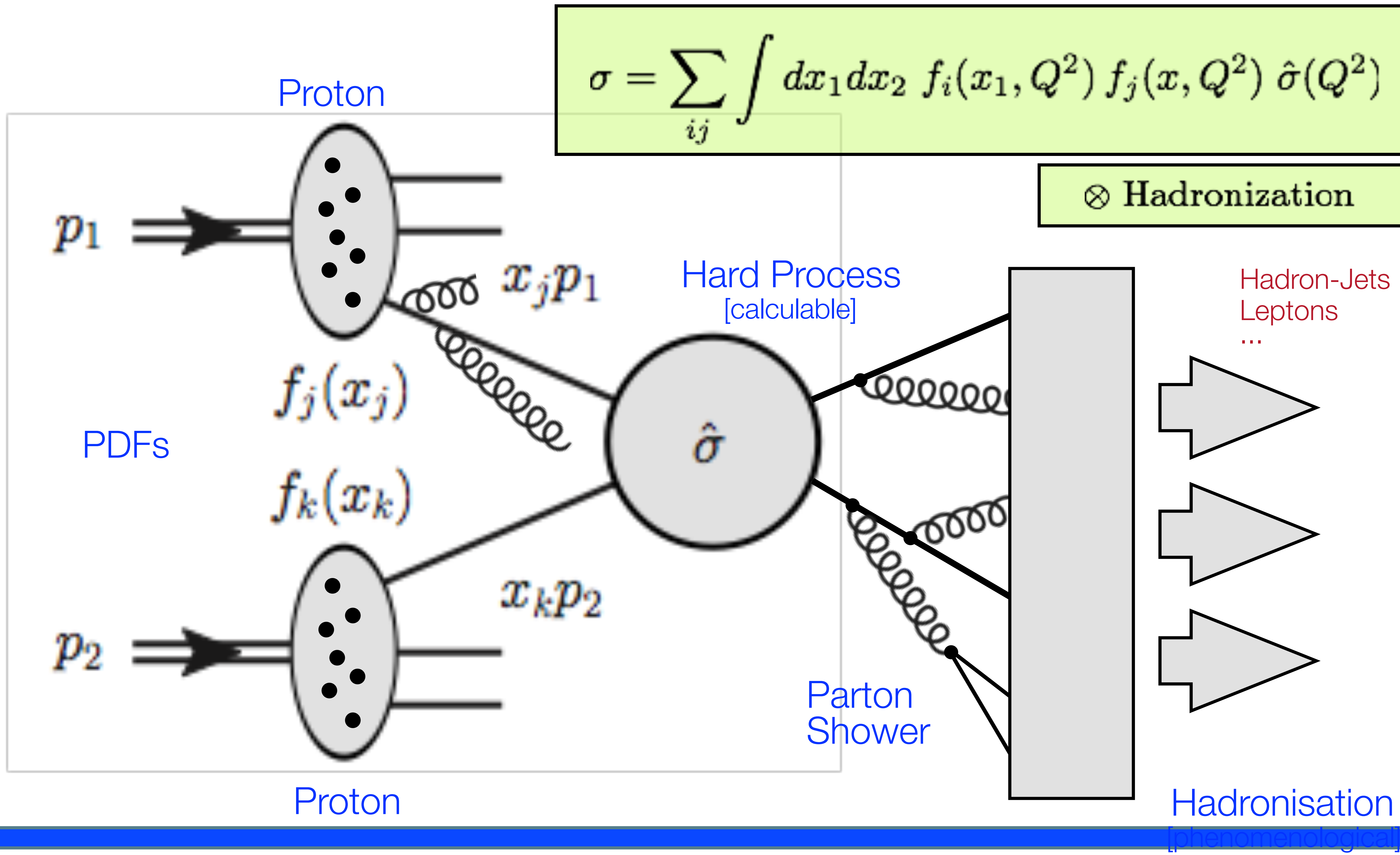
Expected p-value for background hypothesis of a data sample containing SM Higgs boson



Note that ‘peak’ around 160 GeV reflects increased experimental sensitivity not SM prediction of Higgs mass

Conclusions

The simulation chain



MC simulations in particle physics

How Monte Carlo simulation works

- Numerical process generation based on random numbers
- Method very powerful in particle physics

Event Generator
simulate physics process
(quantum mechanics: probabilities!)

Detector Simulation
simulate interaction with detector material

Digitisation
translate interactions with detector into realistic signals

Reconstruction/Analysis
as for real data

Event generation programs:

Pythia6, Pythia8, Herwig, Herwig++, Sherpa ...

Hard partonic subprocess + fragmentation and hadronisation ...

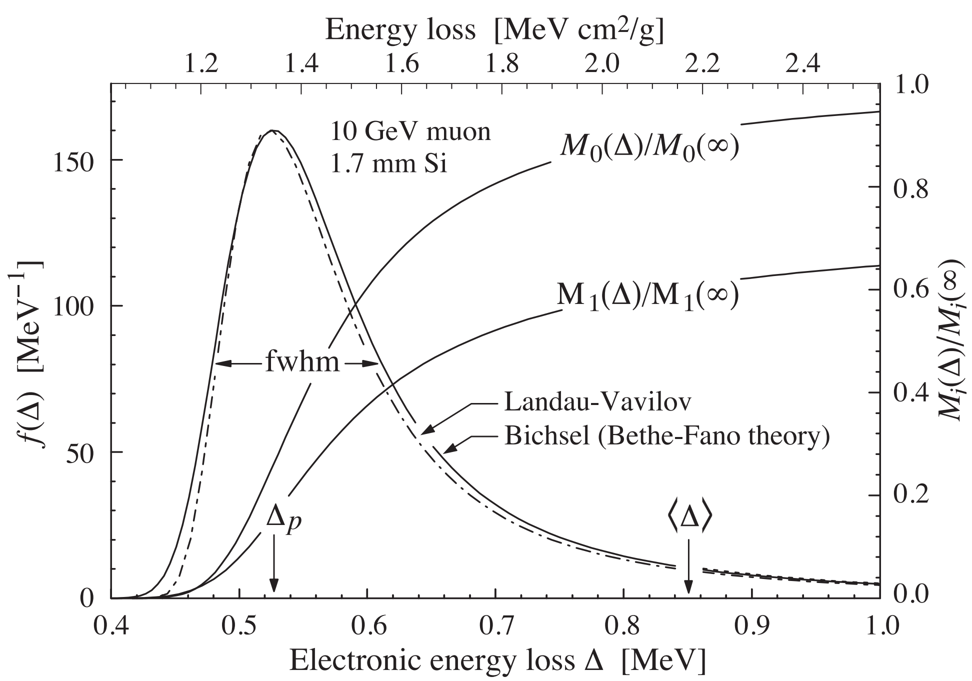
Detector simulation:

Geant4
Fluka low energy hadron interactions...

interaction & response of all produced particles ...

Baseline of the simulation process

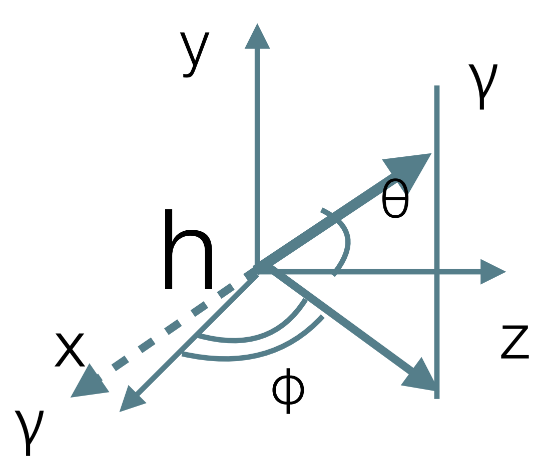
Typically, we need to generate a continuous variable following some distribution
i.e. energy loss of a particle in a given material segment;
angle of a photon in the h reference frame for the h →γγ decay



$$dP = f(x, ..)dx$$

↳ distribution formula

↳ probability to get an x_0 value between x and x+dx



$$dP = f(\theta, \phi)d\theta d\phi = sen\theta d\theta d\phi$$

flat distribution in ϕ
non flat in θ

Distribution function transformation properties

1) software libraries provide basic functions to produce flat distributed random numbers in the interval [0,1] (ex. root TRandom3 class), they are typically fast and accurate uniform random numbers generators;
2) starting from uniform distributed random numbers, it is possible to generate numbers following any distribution using different techniques

$$dP_x = f(x)dx \qquad y = g(x)$$

$$x \in [x_a, x_b]$$

How "y" distributes in [g(x_a), g(x_b)]?

Because y is a monotonic function of x the probability to have y between g(x) and g(x+dx) is equal to the probability to have x between x and x+dx

$$dP_y = h(y)dy = h(y)g'(x)dx$$

$$h(y)g'(x) = f(x) \Rightarrow h(y) = \frac{f(x)}{g'(x)} = \frac{f(g^{-1}(y))}{g'(g^{-1}(y))}$$

Ex.: range map

$$[0,1] \rightarrow [a,b] \qquad y = (b-a)x + a$$

$$f(x) = 1 \quad g'(x) = b - a \quad h(y) = \frac{1}{b-a}$$

uniform

y is uniformly distributed in [a,b]

Distribution function transformation properties

Ex. 2: integration method:

$$g(x) = \frac{1}{\int_a^b f(x')dx'} \int_a^x f(x')dx' \qquad g'(x) = \frac{f(x)}{\int_a^b f(x')dx'}$$

$$h(y) = \frac{f(x)}{g'(x)} = \frac{f[g^{-1}(y)]}{f[g^{-1}(y)]} \cdot \int_a^b f(x')dx' = \int_a^b f(x')dx'$$

y is uniformly distributed:

1) generate y flat in [f_{min}, f_{max}];
2) compute x = $g^{-1}(y)$, x will be distributed in $g^{-1}(f_{min})$, $g^{-1}(f_{max})$

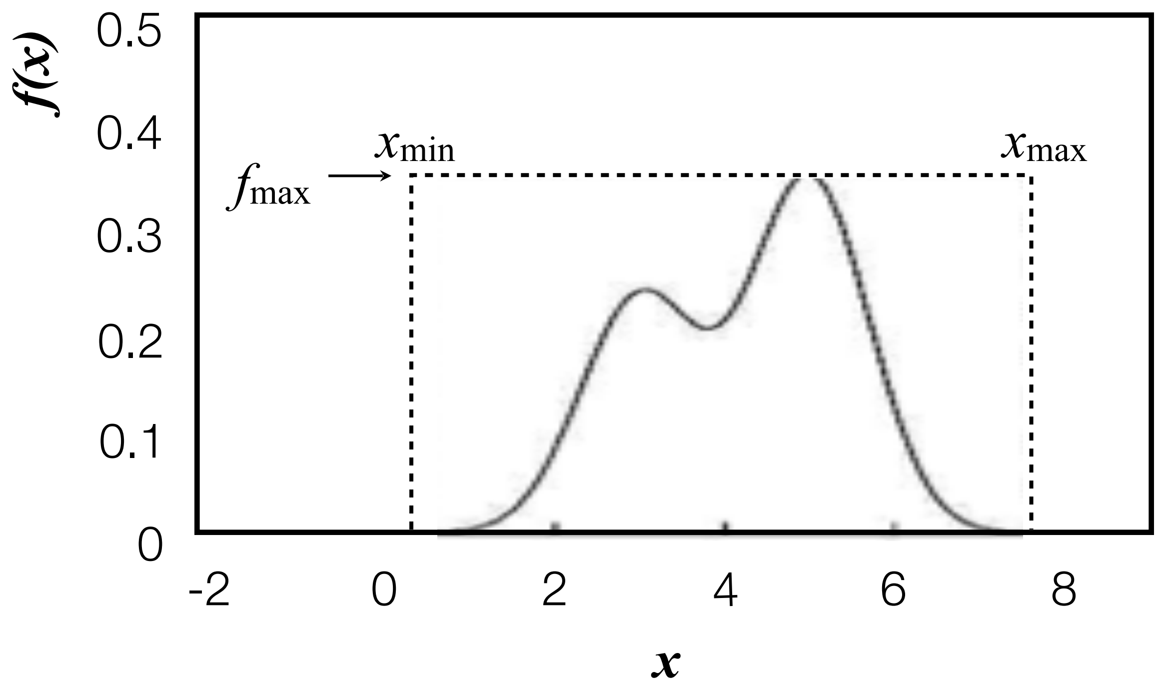
Finding $g^{-1}(y)$ is equivalent to solve the equation:

$$\frac{1}{\int_a^b f(x')dx'} \int_a^x f(x')dx' = y$$

Hit or miss method.

1) generate x flat in x_{min}, x_{max}
2) generate y flat in 0, f_{max}
3) if y < f(x) accept the event, otherwise ignore it

for a given x in x, x+dx the fraction of accepted events is proportional to f(x)dx -> dPx = f(x)dx



1) advantages:

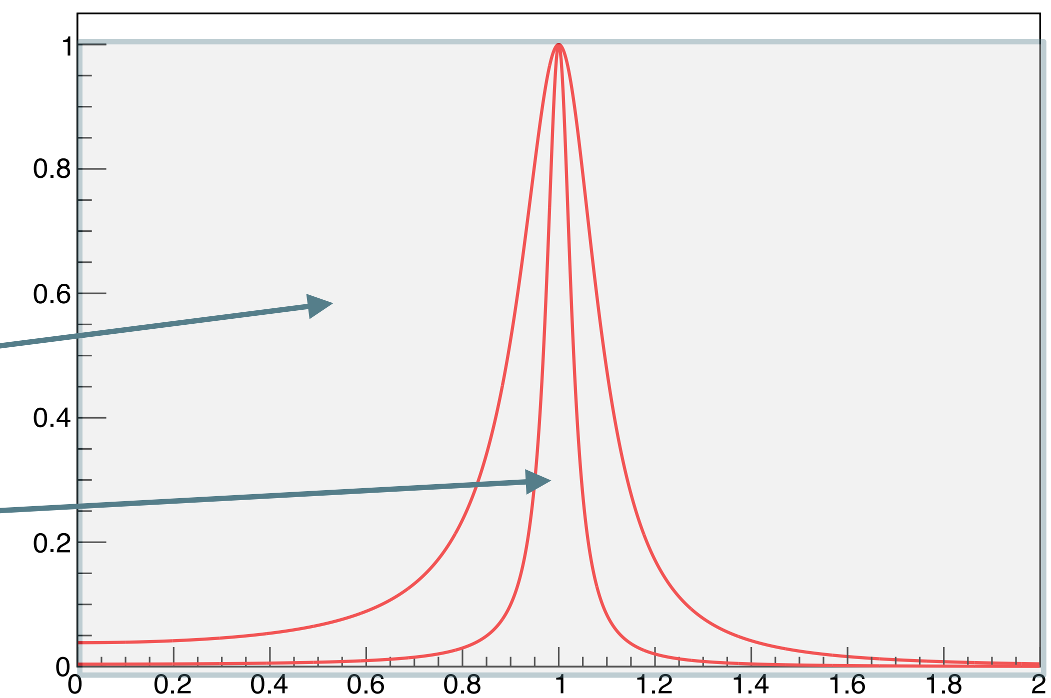
- can be used for all functions, even non continuous …
- can be extended to N-dimension (generate $x_1, x_2, \ldots, x_n$), y accept if $y < f(x_1, x_2, .., x_n)$

2) disadvantages

- can be extremely slow

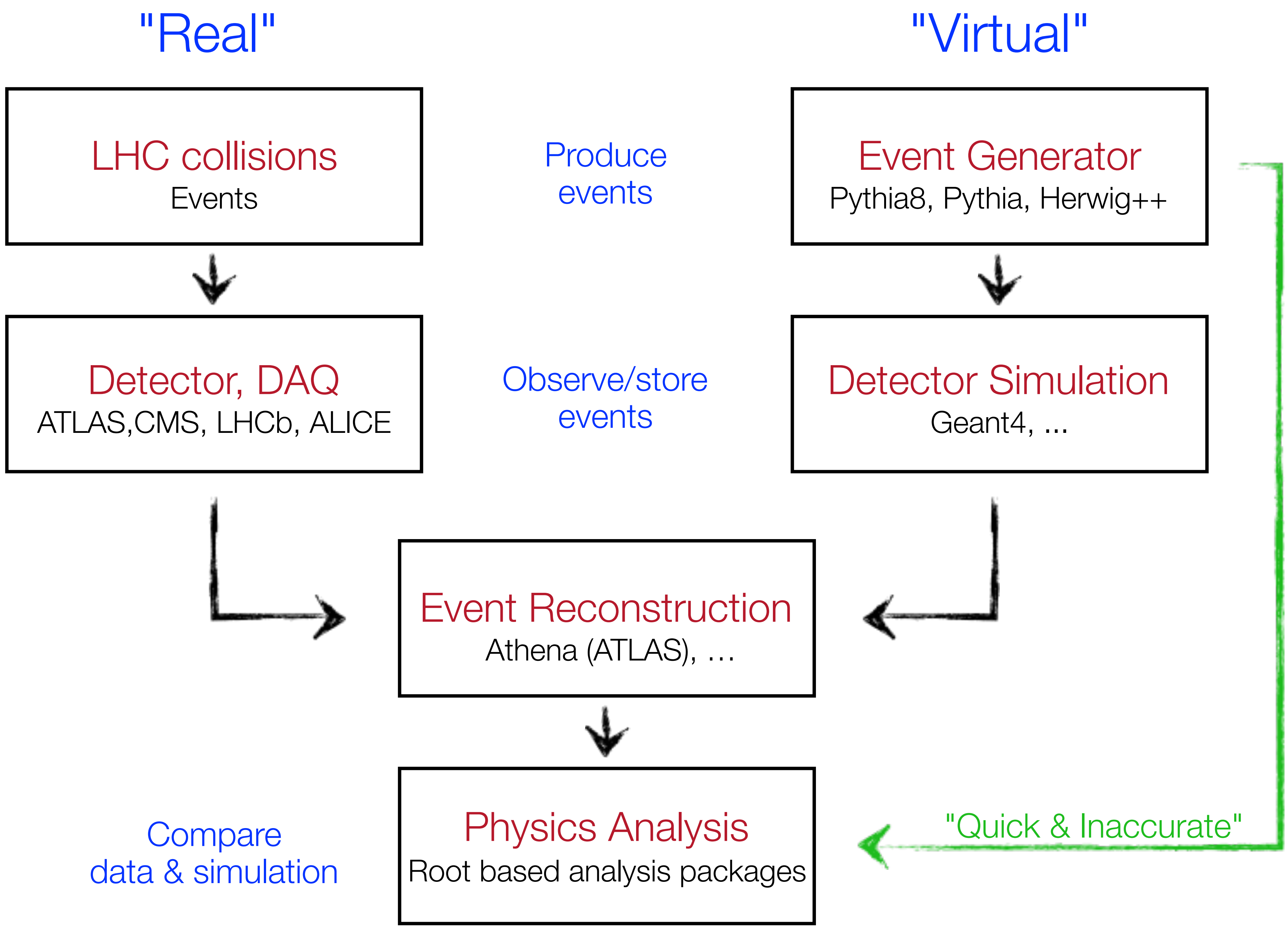
points generated uniformly in the square

points accepted only below the curve



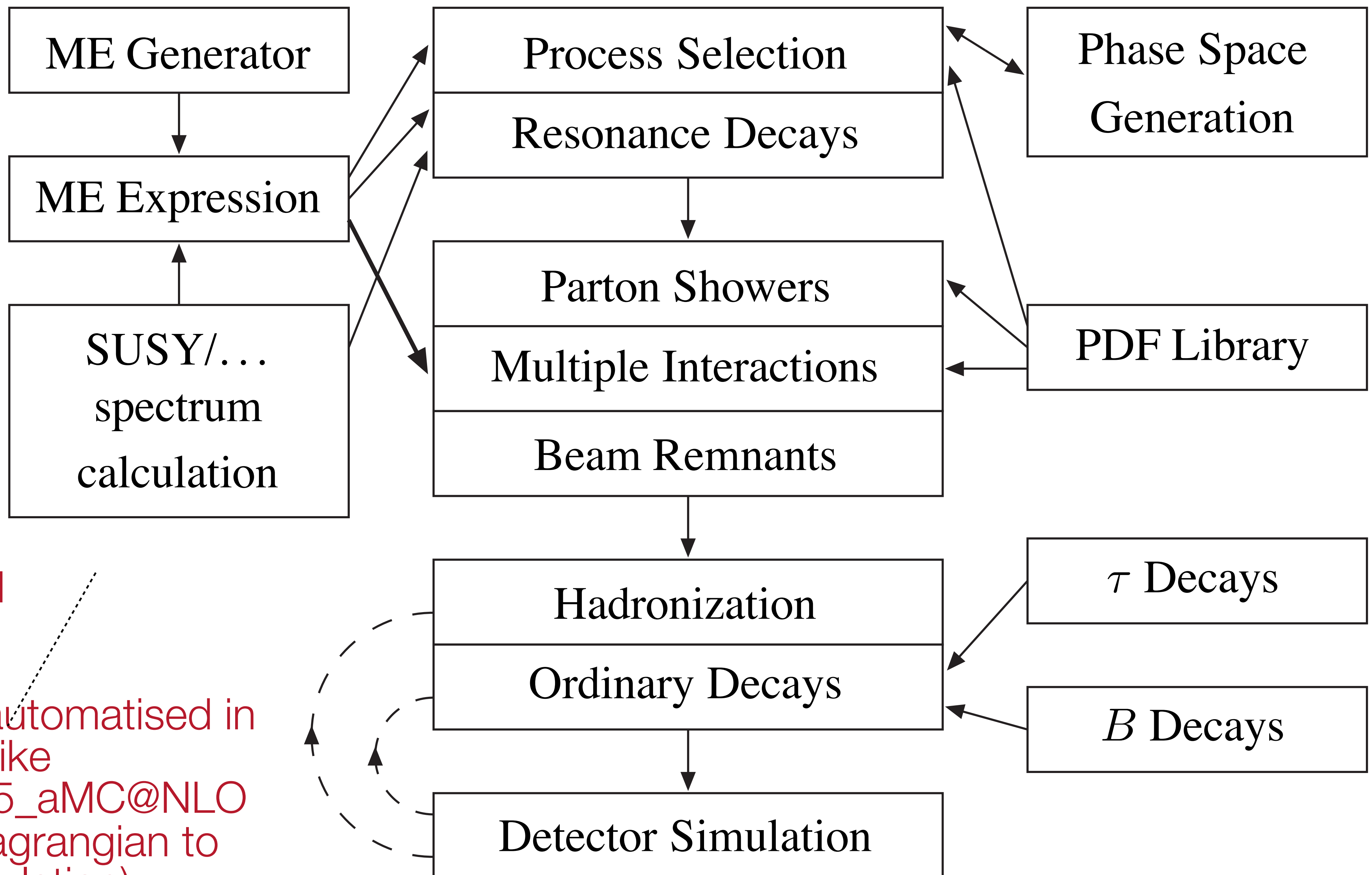
MC generators implement “smart” generation techniques to increase efficiencies

Comparison between real and simulated events



[after T.Sjöstrand]

Simulation elements

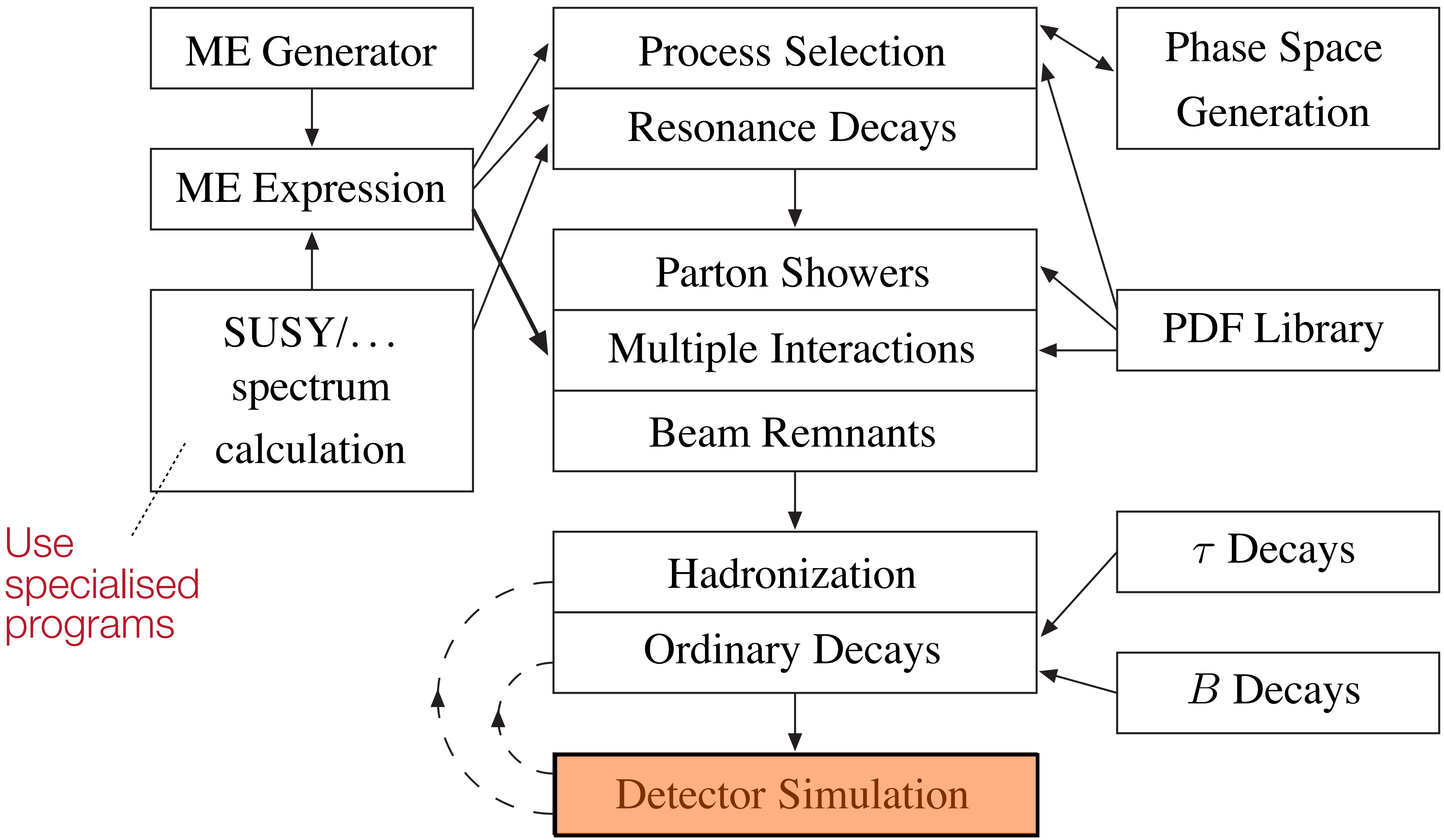


Use specialised programs

Now fully automatised in programs like Madgraph5_aMC@NLO (from the lagrangian to the full simulation)

[Sjöstrand, arXiv:hep-ph/0611247v1]

Simulation elements



[Sjöstrand, arXiv:hep-ph/0611247v1]

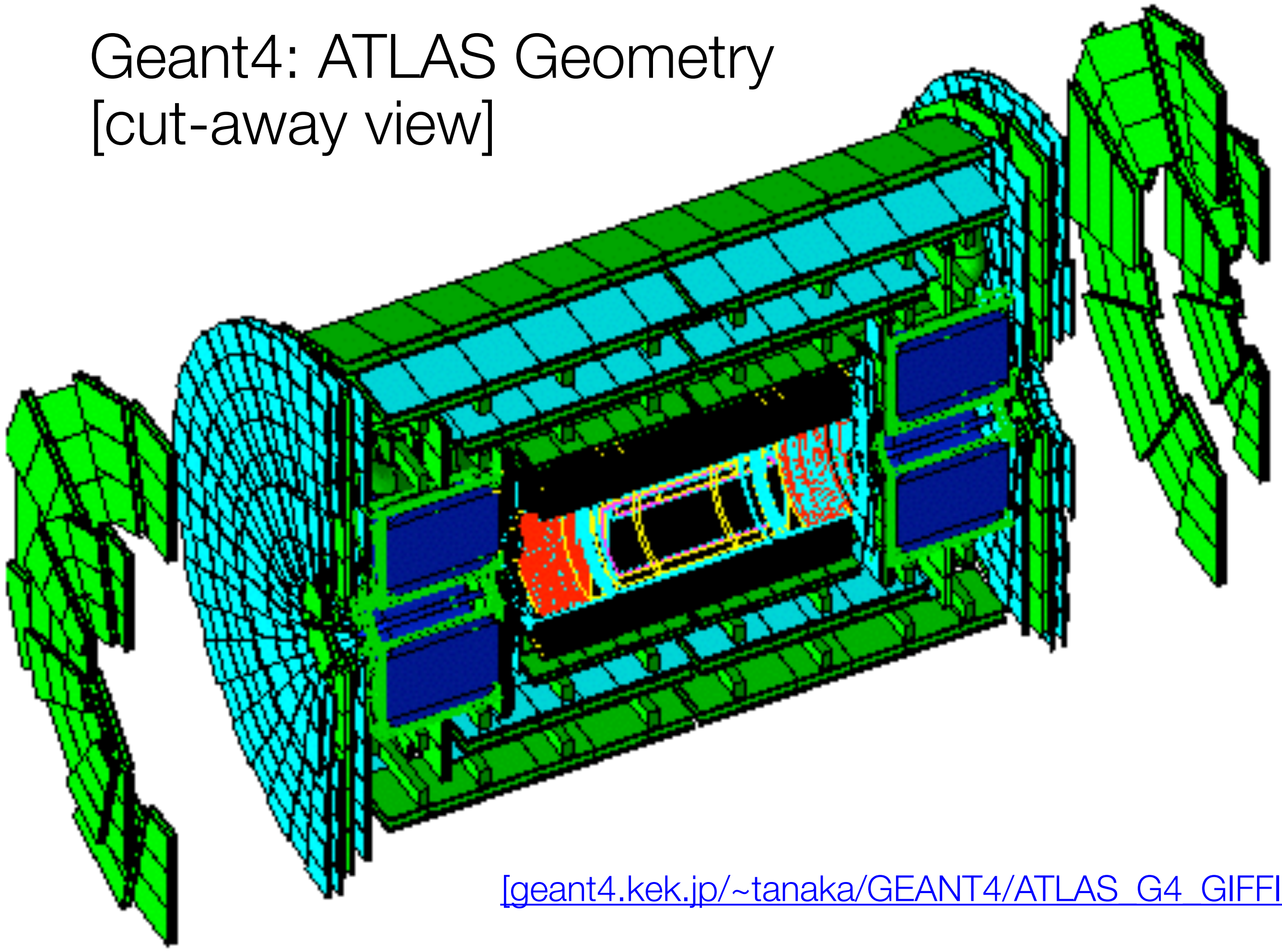
GEANT Geometry And Tracking

Detailed description of detector geometry
[sensitive & insensitive volumes]

Tracking of all particles through detector material ...

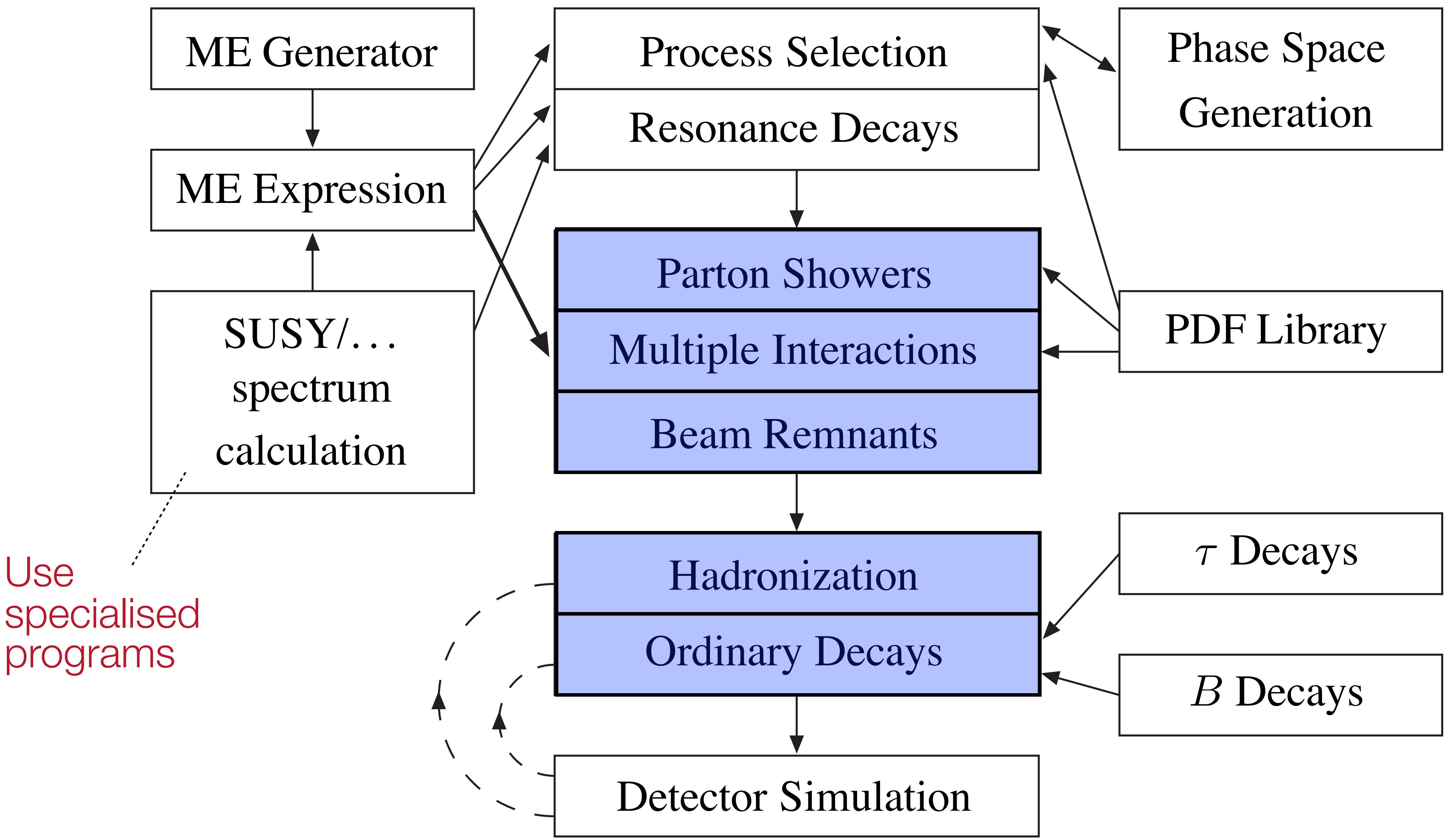
➛ Detector response

Geant4: ATLAS Geometry
[cut-away view]



[geant4.kek.jp/~tanaka/GEANT4/ATLAS_G4_GIFFIG/]

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C^{++}]



[Sjöstrand, arXiv:hep-ph/0611247v1]

Strong interactions:

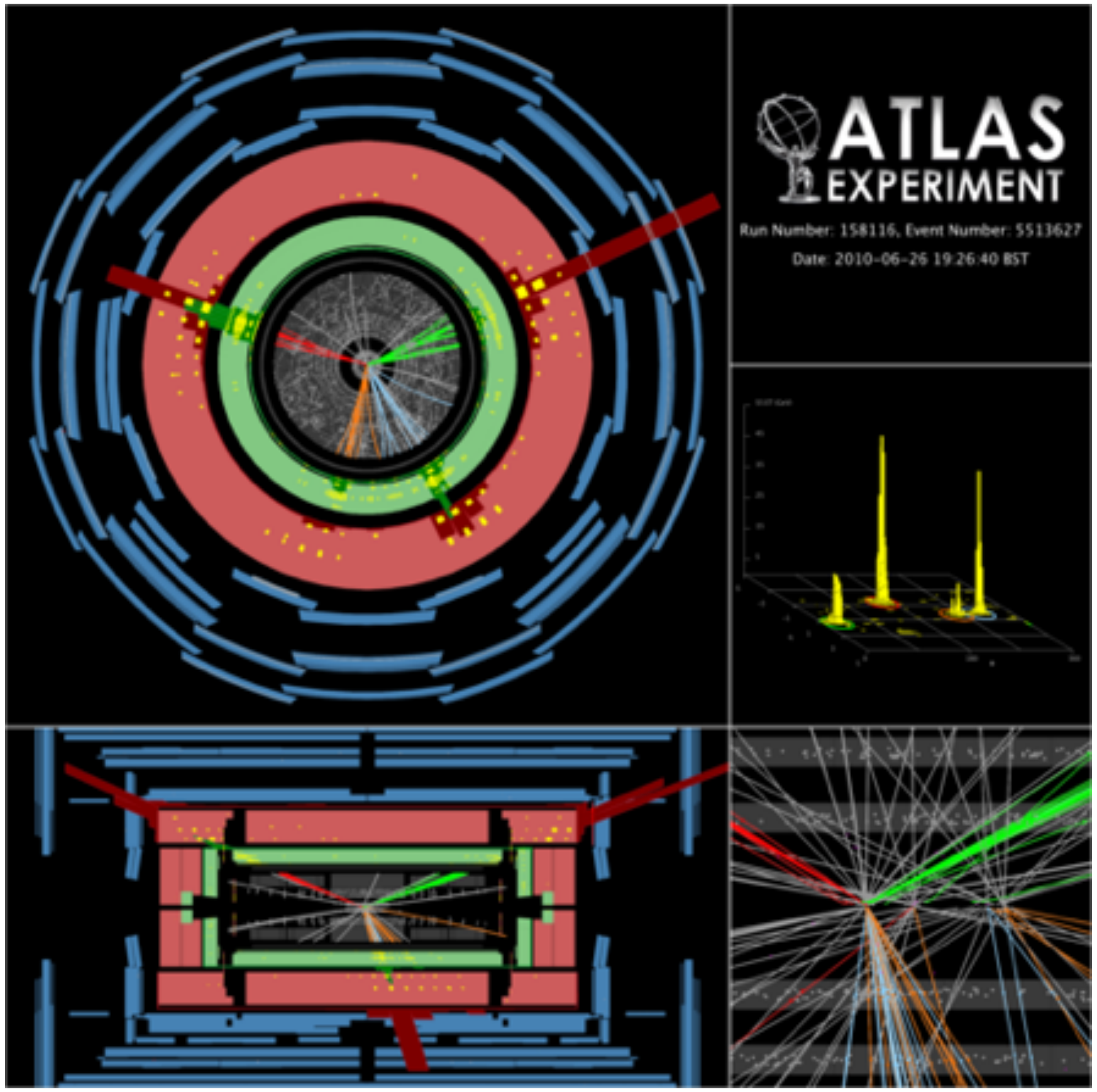
No free Quarks

Expect jets

i.e. bundles of particles at high energies
[hadron p_T range limited w.r.t. initial parton]

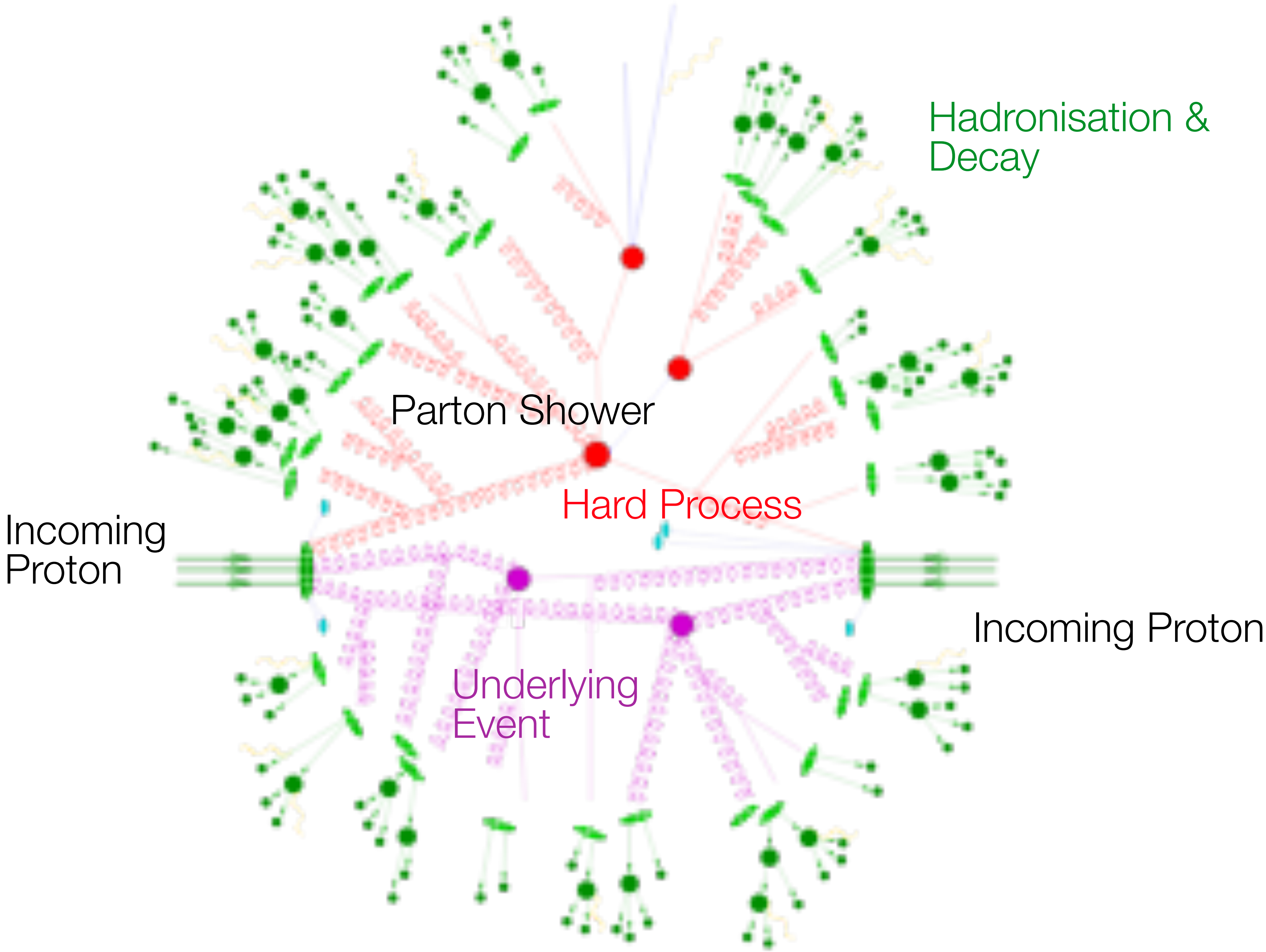
First observation of jets
in e^+e^- collisions @ $E_{CMS} > 6$ GeV
[SPEAR, SLAC, 1975]

Later also observed in
hadron-hadron collisions
[e.g. @ CERN ISR]



An event with 4 jets @ LHC

Goal: Infer parton properties from jet properties
[need to calculate and/or model fragmentation & hadronisation process]



[T. Gleisberg et al., JHEP02 (2004) 056]

Pure matrix element (ME) simulation:

MC integration of cross section & PDFs, no hadronisation
(recall: cross section = $|\text{matrix element}|^2 \otimes$ phase space)

Useful for theoretical studies, no exclusive events generated

[Example: MCFM (http://mcfm.fnal.gov); many LHC processes up to NLO,
HNNLO (http://theory.fi.infn.it/grazzini/codes.html) Higgs production at NNLO]

Event generators:

Combination of ME and parton showers ...

Typical: generator for leading order ME
combined with leading log (LL) parton shower MC (see later)

Exclusive events ➛ useful for experimentalists ...

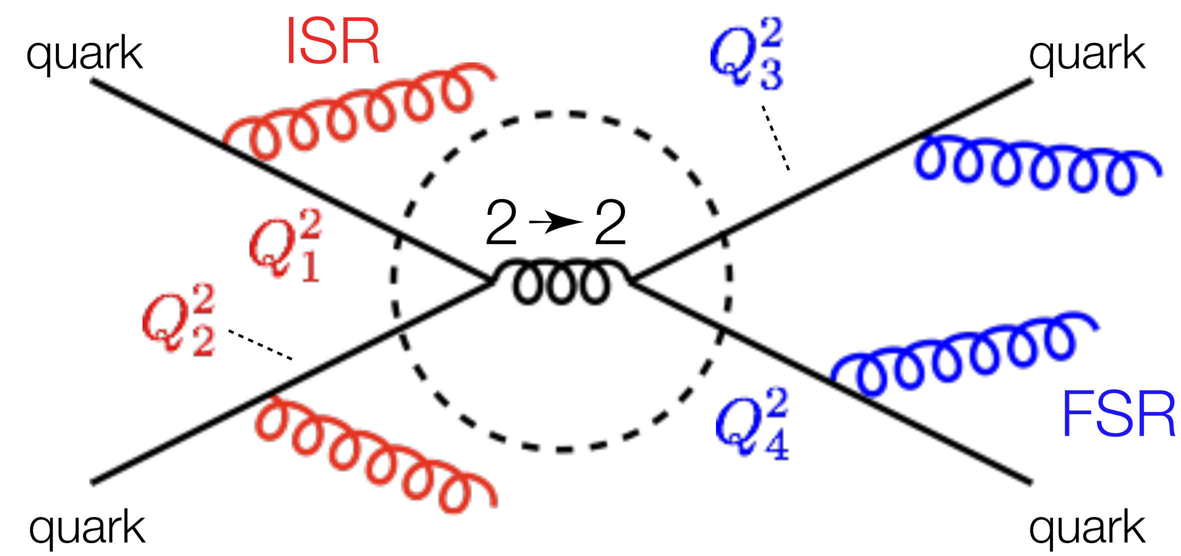
Parton showers

[Sjöstrand, arXiv:hep-ph/0611247v1]

A realistic simulation needs many particles in the final state, it is quite difficult (sometimes impossible) to compute a pp (2) → many particles process

(2 ➛ n) = ...

... = (2 ➛ 2) ⊕ ISR ⊕ FSR



FSR: Final state radiation
$Q^2 \sim m^2 > 0$ decreasing
[time-like shower]

ISR: Initial state radiation
$Q^2 \sim -m^2 > 0$ increasing
[space-like shower]

Calculable

Hard process [2 ➛ 2]:

$$\sigma = \iiint \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}\hat{t}\; f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}\hat{t}}$$

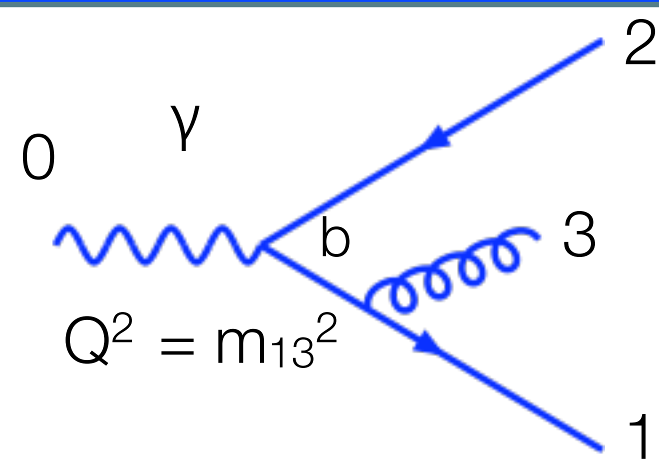
Shower evolution:

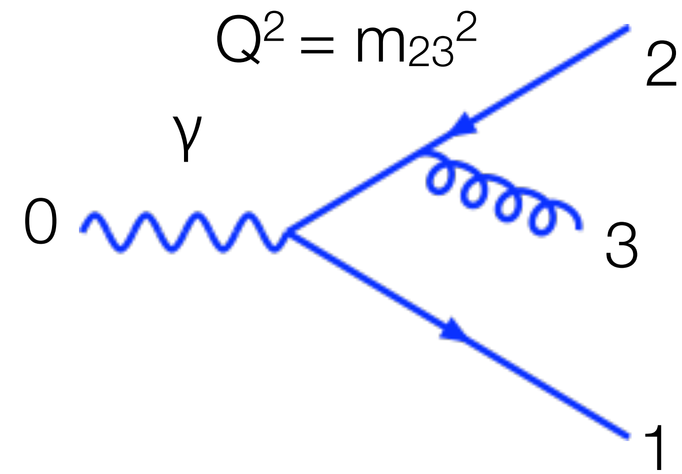
Viewed as probabilistic process, which occurs with unit total probability;
cross section not directly affected; only indirectly via changed event shape.

[Sjöstrand, arXiv:hep-ph/0611247v1]

Parton showers

$e^+e^- \to qqg$





$$x_i = \frac{2E_i}{E_{\text{cm}}} \qquad x_1 + x_2 + x_3 = 2$$

Cross Section: $$\frac{d\sigma_{\text{qqg}}}{dx_1 dx_2} = \frac{4}{3}\frac{\alpha_s}{2\pi} \cdot \sigma_0 \cdot \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

Cross section has large contributions for $x_1, x_2 \to 1$

[$m_q = 0$; see e.g. Halzen/Martin]

from p_T balance $$1 - x_2 = \frac{m_{13}^2}{E_{\text{cm}}^2} = \frac{Q^2}{E_{\text{cm}}^2} \quad m_{13}^2 \sim 2E_1E_2(1-cos\theta)\, x_2 \to 1 \Rightarrow m_{13}^2 \to 0 \quad \Longrightarrow \quad \theta \to 0 \text{ collinear limit}$$

$$dx_2 = -\frac{dQ^2}{E_{\text{cm}}^2}$$

Rewrite for $x_2 \to 1$:

[qg collinear limit]

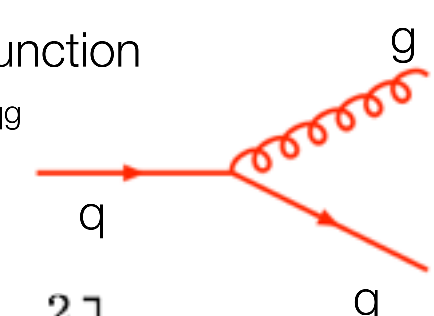
$$x_1 \approx z \qquad dx_1 \approx dz$$

$$x_3 \approx 1 - z$$

$$E_q = E_1 = zE_b \quad E_g = E_3 = (1-z)E_b$$

Splitting Function

$P_{q\to qg}$



$$d\mathcal{P} = \frac{d\sigma_{\text{qqg}}}{\sigma_0} = \frac{4}{3}\frac{\alpha_s}{2\pi} \cdot \frac{dx_2}{(1-x_2)} \cdot \frac{x_1^2 + x_2^2}{(1-x_1)} dx_1 \approx \frac{\alpha_s}{2\pi} \cdot \frac{dQ^2}{Q^2} \cdot \frac{4}{3}\left[\frac{1+z^2}{1-z}\right] dz$$

$z \to 1 \Rightarrow E_g \to 0$ soft divergence

$$d\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)dz$$

Splitting probability determined by splitting functions $P_{q\to qg}$

Analogous splitting functions used in PDF evolution

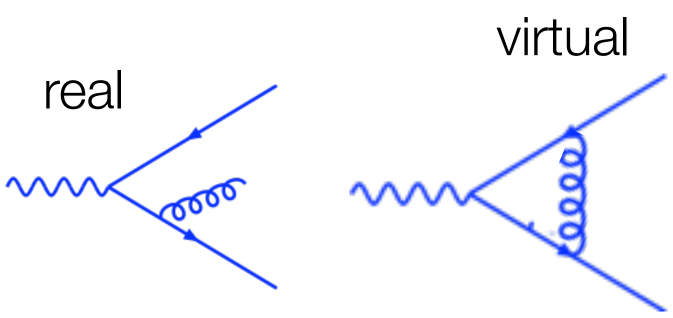
$$P_{q\to qg} = \frac{4}{3}\frac{1+z^2}{1-z}$$

$$P_{g\to gg} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$

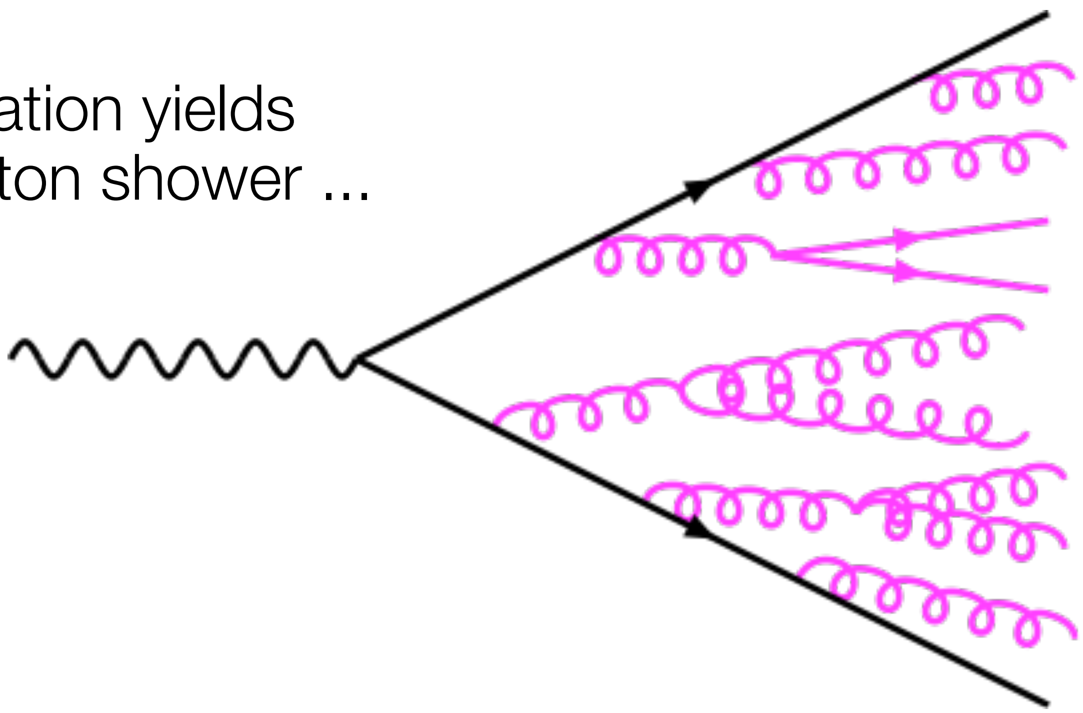
$$P_{g\to q\bar{q}} = \frac{n_f}{2}(z^2+(1-z)^2)$$

z : fractional momentum of radiated parton
n_f : number of quark flavours

In NLO calculations soft and collinear divergencies cancelled by virtual contributions: they persist in LO calculations.



Iteration yields parton shower ...



Need soft/collinear cut-offs to avoid non-perturbative regions ... [divergencies!]

Details model-dependent

e.g. $Q > m_0 = \min(m_{ij}) \approx 1$ GeV,
$z_{min}(E,Q) < z < z_{max}(E,Q)$ or
$p_\perp > p_{\perp min} \approx 0.5$ GeV

Parton shower evolution 1

[Sjöstrand, arXiv:hep-ph/0611247v1]

Conservation of total probability:

$$\mathcal{P}(\text{nothing happens}) = 1 - \mathcal{P}(\text{something happens})$$

Time evolution:

$$\mathcal{P}_{\text{nothing}}(0 < t \le T) = \mathcal{P}_{\text{nothing}}(0 < t \le T_1)\, \mathcal{P}_{\text{nothing}}(T_1 < t \le T)$$

$$\begin{aligned}
\mathcal{P}_{\text{nothing}}(0 < t \le T) &= \lim_{n\to\infty} \prod_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \le T_{i+1}) \\
&= \lim_{n\to\infty} \prod_{i=0}^{n-1} (1 - \mathcal{P}_{\text{something}}(T_i < t \le T_{i+1})) \\
&= \exp\left(- \lim_{n\to\infty} \sum_{i=0}^{n-1} \mathcal{P}_{\text{something}}(T_i < t \le T_{i+1}) \right) \\
&= \exp\left(- \int_0^T \frac{\mathrm{d}\mathcal{P}_{\text{something}}(t)}{\mathrm{d}t} \mathrm{d}t \right)
\end{aligned}$$

$e^{-x} \approx 1 - x$

[Taylor]

➛ $$\mathrm{d}\mathcal{P}_{\text{first}}(T) = \mathrm{d}\mathcal{P}_{\text{something}}(T)\, \exp\left(- \int_0^T \frac{\mathrm{d}\mathcal{P}_{\text{something}}(t)}{\mathrm{d}t} \mathrm{d}t \right)$$

Parton shower evolution 2

[Sjöstrand, arXiv:hep-ph/0611247v1]

Instead of evolving to later and later times
need to evolve to smaller and smaller Q^2 ...
[Heisenberg: Q ~ 1/t]

Sudakov Form Factor

$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2} P_{a\to bc}(z)\,\mathrm{d}z\ \exp\left(-\sum_{b,c}\int_{Q^2}^{Q^2_{\max}}\frac{\mathrm{d}Q'^2}{Q'^2}\int\frac{\alpha_s}{2\pi}P_{a\to bc}(z')\,\mathrm{d}z'\right)$$

Probability to radiated with virtuality Q^2

No radiation for higher virtualities i.e. for Q^2 ... Q^2_{max}

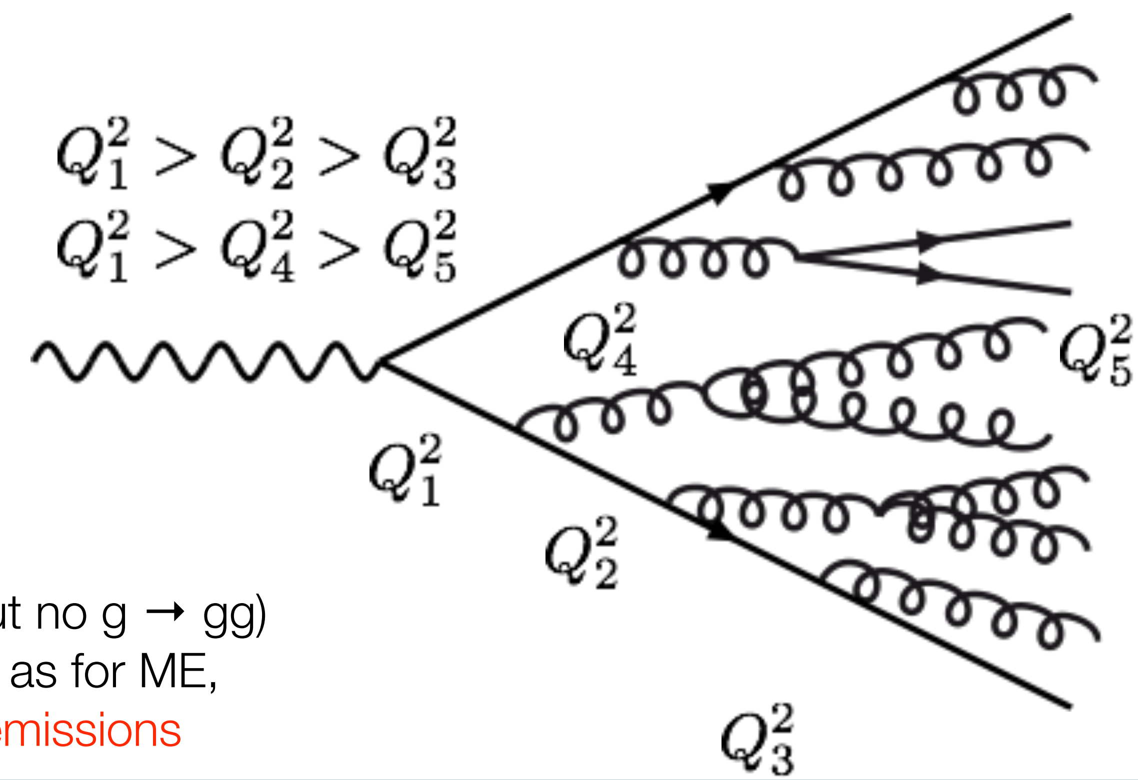
Note that $\sum_{b,c} \iint dP_{a\to bc} \equiv 1$...
[Convenient for Monte Carlo]

Sudakov form factor ...

... provides "time" ordering of shower ...
[lower Q^2 ⇔ longer times]

... regulates singularity for first emission ...

But in the limit of repeated soft emissions q → qg (but no g → gg)
one obtains the same inclusive Q emission spectrum as for ME,
i.e. divergent ME spectrum ⇔ infinite number of PS emissions



Sudakov picture of parton showers

Basic algorithm: Markov chain

[each step requires only knowledge only of previous step]

(i) Start with virtuality Q_1 and momentum fraction x_1

(ii) Generate target virtuality Q_2 with random number R_T uniform distributed in [0,1]

Probability to not have $Q_x > Q_2$

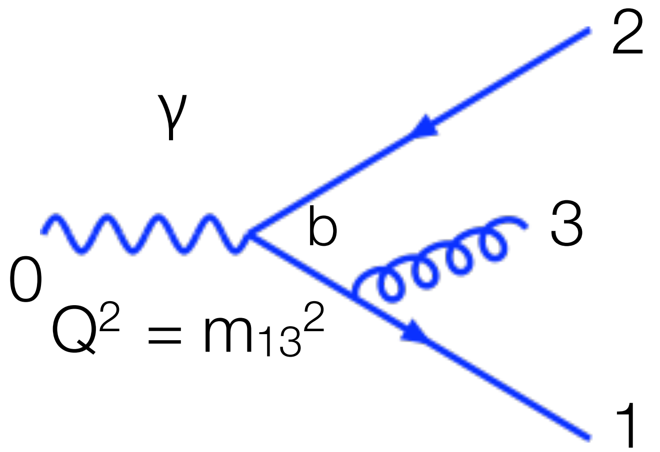
using:

$$\Delta(Q_i^2) = \exp\left(-\sum_{b,c}\int_{Q_i^2}^{Q^2_{\max}} \frac{dQ'^2}{Q'^2}\int \frac{\alpha_s}{2\pi} P_{a\to bc}(z')\,dz'\right)$$

solve the equation for Q_2

$$R_t = \frac{\Delta(Q_2^2)}{\Delta(Q_1^2)}$$

[probability to evolve from t_1 to t_2 without radiation]



(iii) Q_2 known (x_2 known), need to compute $x_1 \sim z$

$$P_{\mathrm{q}\to\mathrm{qg}} = \frac{4}{3}\frac{1+z^2}{1-z}$$

$$R_z = \frac{\int_0^z P(z')dz'}{\int_0^1 P(z')dz'}$$

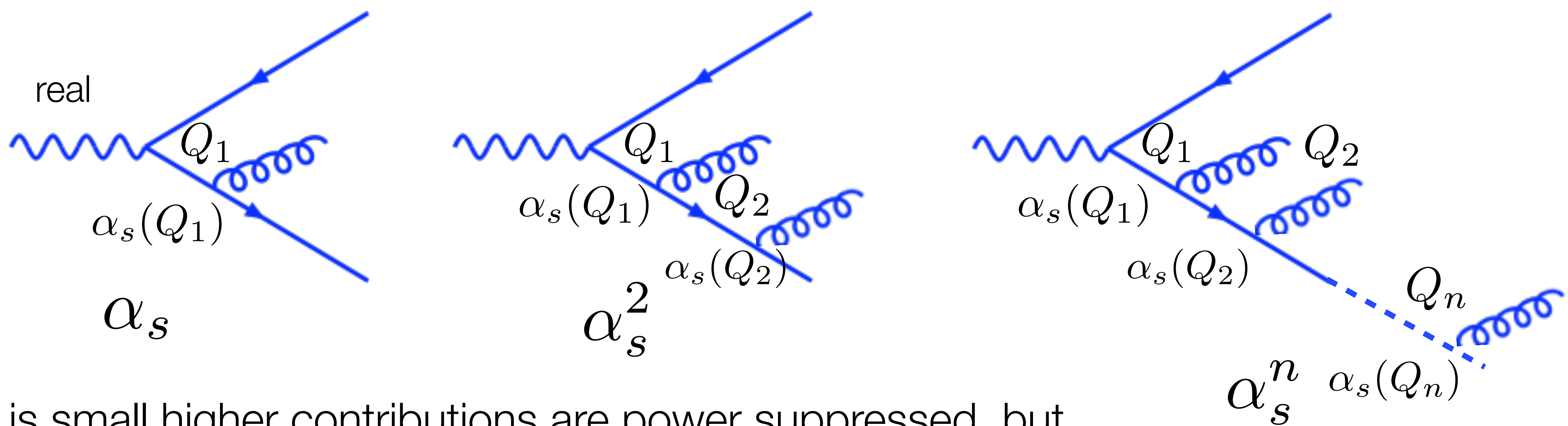
flat distributed

$$R_z \in [0,1]$$

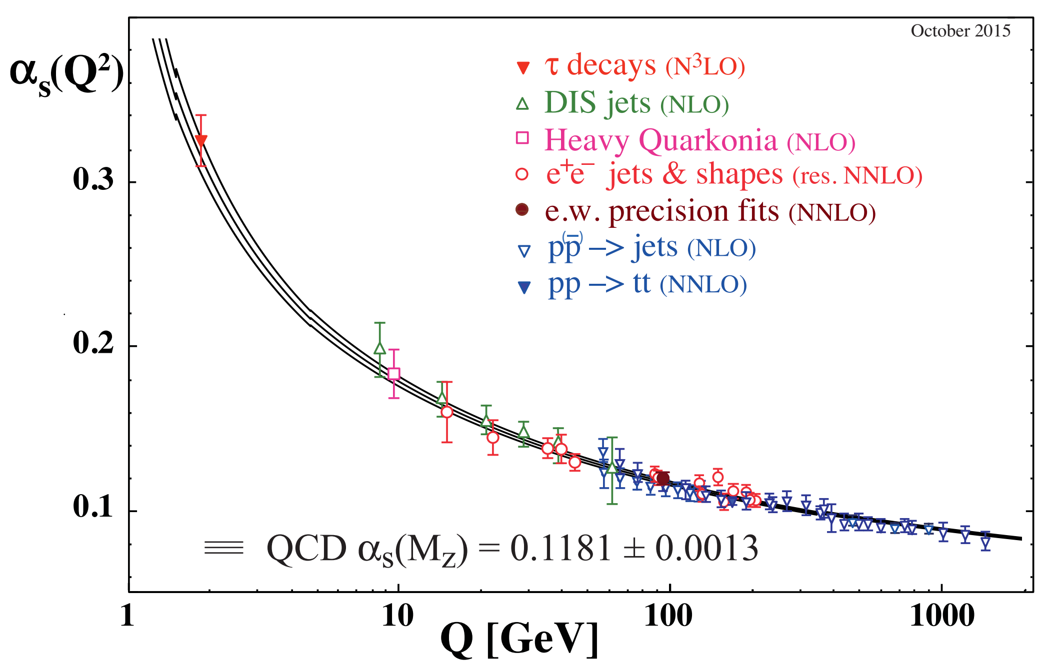
(iv) Generate random azimuthal angle Φ flat distributed

Process ends when partons are below threshold (p_T,Q)

Parton shower and logarithmic resummation



If α_s is small higher contributions are power suppressed, but…



α_s increases at small Q^2

$$\alpha_s(Q_n) \sim \alpha_s(Q_1) ln(Q_1/Q_n)$$

$$\alpha_s(Q_1) + \alpha_s(Q_1)\alpha_s(Q_2) + ... + \alpha_s(Q_1) \cdot ... \cdot \alpha_s(Q_n)$$

$$\sim [\alpha_s(Q_1) ln(Q_1)]^2 \sim [\alpha_s(Q_1) ln(Q_1)]^n$$

if $\alpha_s(Q_1) ln(Q_1)$ is large, the expansion is broken, PS allow to sum up all the large contribution [Leading Log resummation]

Parton shower ordering

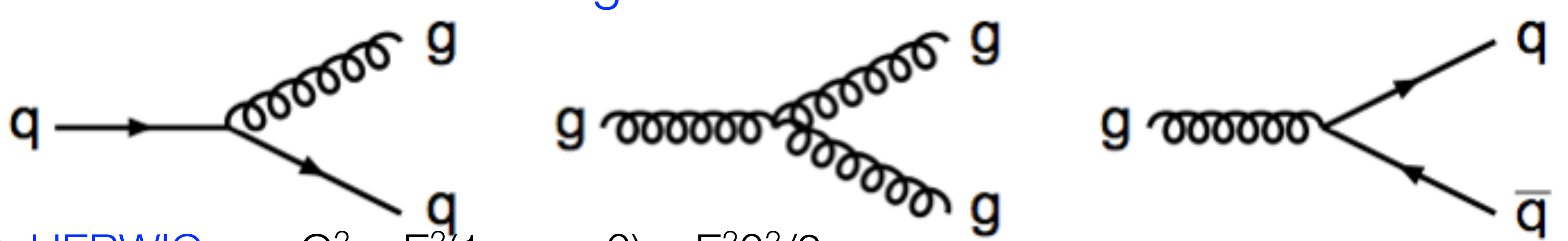
$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2}P_{a\to bc}(z)\,\mathrm{d}z\,\exp\left(-\sum_{b,c}\int_{Q^2}^{Q^2_{\max}}\frac{\mathrm{d}Q'^2}{Q'^2}\int\frac{\alpha_s}{2\pi}P_{a\to bc}(z')\,\mathrm{d}z'\right)$$

In the splitting function appears only dQ^2/Q^2, therefore if $P = f(z)Q^2$ $dP/P = dQ^2/Q^2$

Three main approaches to showering in use:

$p_\perp^2 \approx z(1-z)m^2$ p_T ordered showers $E^2\theta^2 \approx m^2/(z(1-z))$ angular ordered showers

Two are based on the standard shower language of a ➛ bc successive branchings:

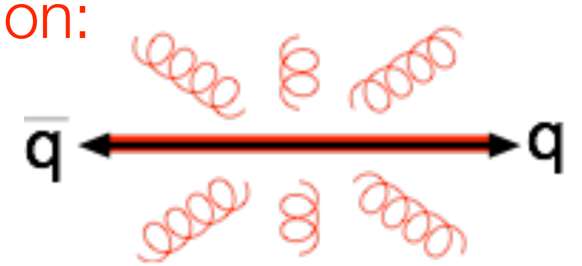


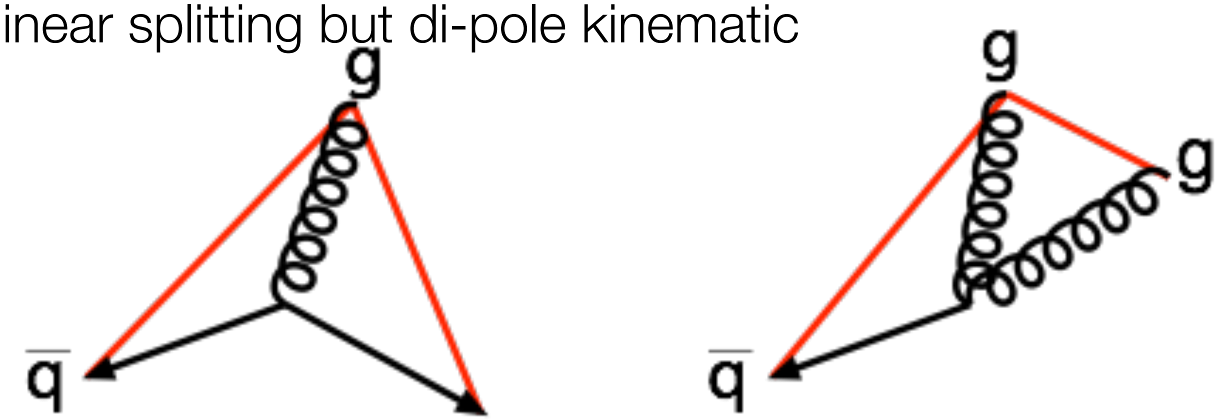
HERWIG, HERWIG++ : $Q^2 \approx E^2(1 - \cos\theta) \approx E^2\theta^2/2$

PYTHIA, 8 (basic) : $Q^2 = m^2$ (timelike) or $= -m^2$ (spacelike)

PYTHIA6, 8 (p_T oredered) : mixture: collinear splitting but di-pole kinematic

One is based on a picture of dipole emission:

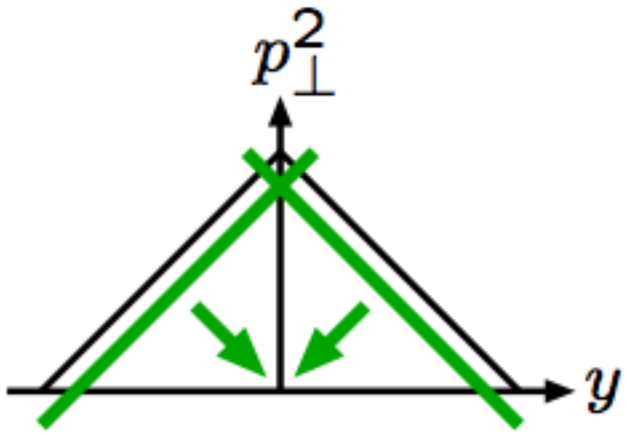




Ariadne : $Q^2 = p^2_\perp$; FSR mainly, ISR is primitive ... consider the full recoil and not only the branching

[from G.Herten]

PYTHIA: $Q^2 = m^2$

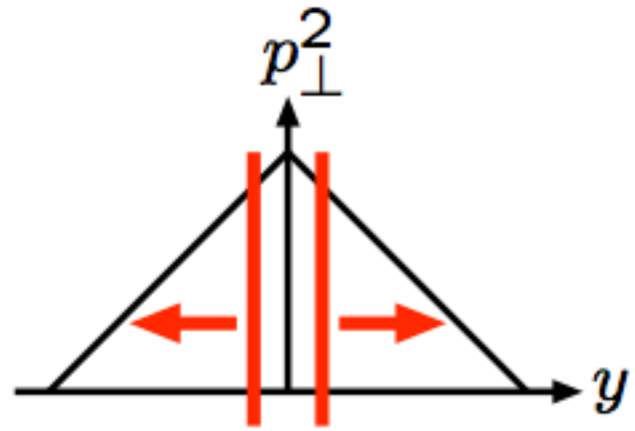


Large mass first
["hardness" ordered]

Covers phase space
ME merging simple
g ➛ qq simple
not Lorentz invariant
no stop/restart

ISR: $m^2 \rightarrow -m^2$

HERWIG/++: $Q^2 \sim E^2\theta^2$

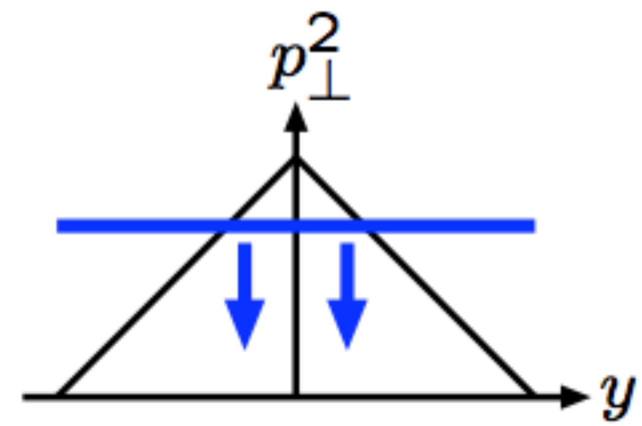


Large angle first
[not "hardness" ordered]

Gaps in coverage
ME merging messy
g ➛ qq simple
not Lorentz invariant
no stop/restart

ISR: $\theta \rightarrow \theta$

ARIADNE/Pythia8: $Q^2 = p^2_\perp$



Large $p_\perp$ first
["hardness" ordered]

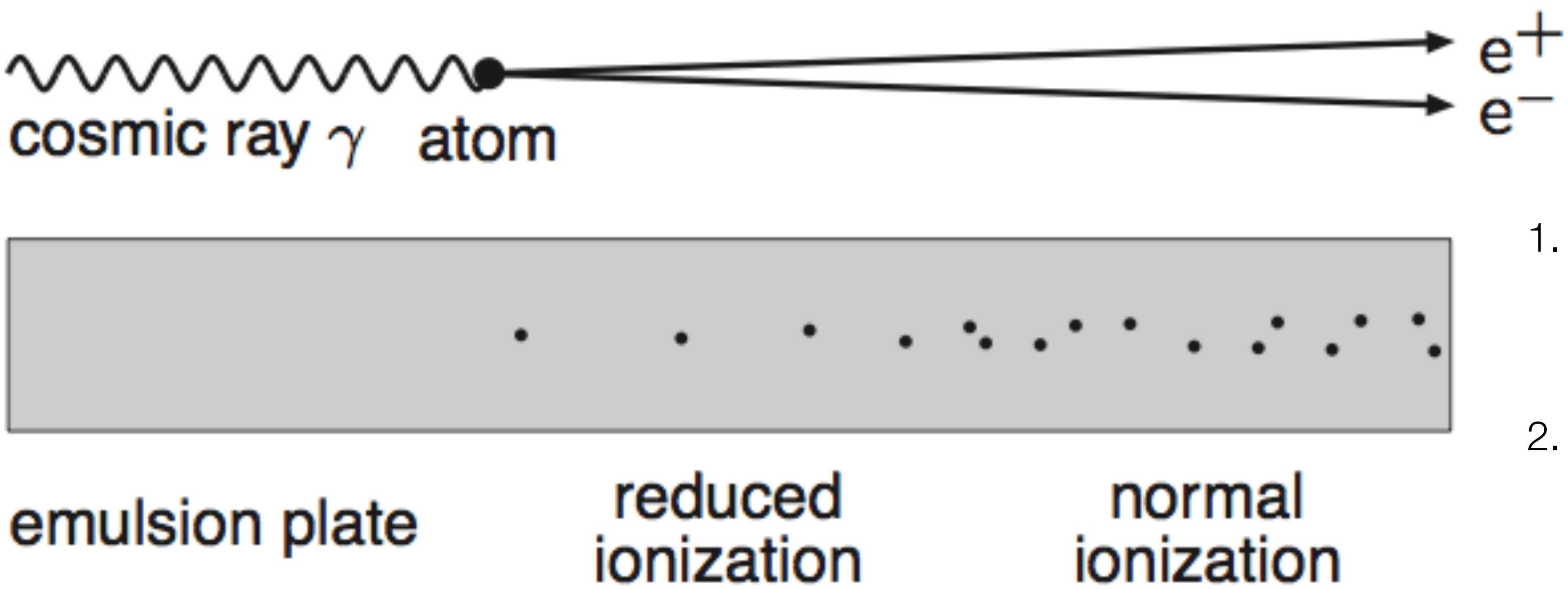
Covers phase space
ME merging simple
g ➛ qq messy
Lorentz invariant
can stop/restart

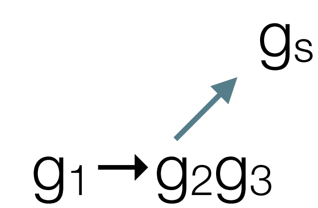
ISR: complicated

[from G.Herten]

Color coherence

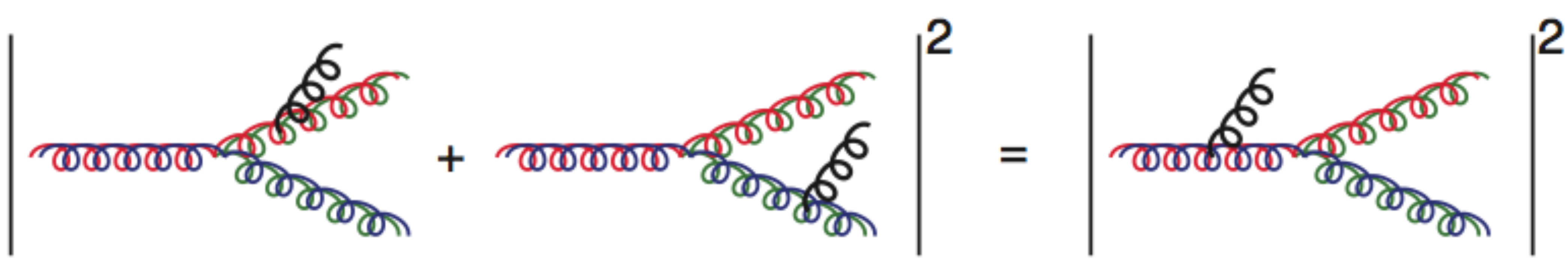
QED: Chudakov effect (mid-fifties)





1. soft gluons see the pair of split gluons as a whole, color screening reduce their emission
2. angular ordered and p_T ordered PS reproduce the correct color coherence
3. Pythia Q^2 needs aposteriori corrections

QCD: colour coherence for **soft** gluon emission



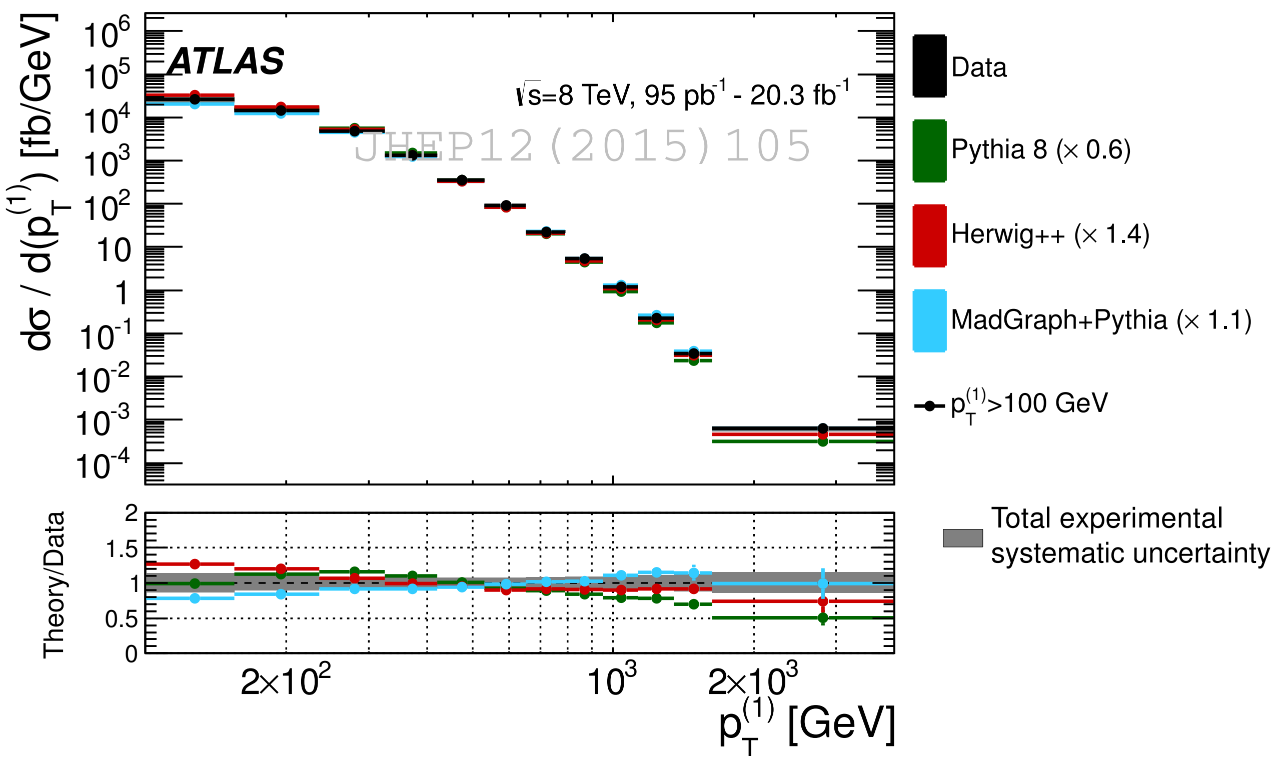
solved by
- requiring emission angles to be decreasing

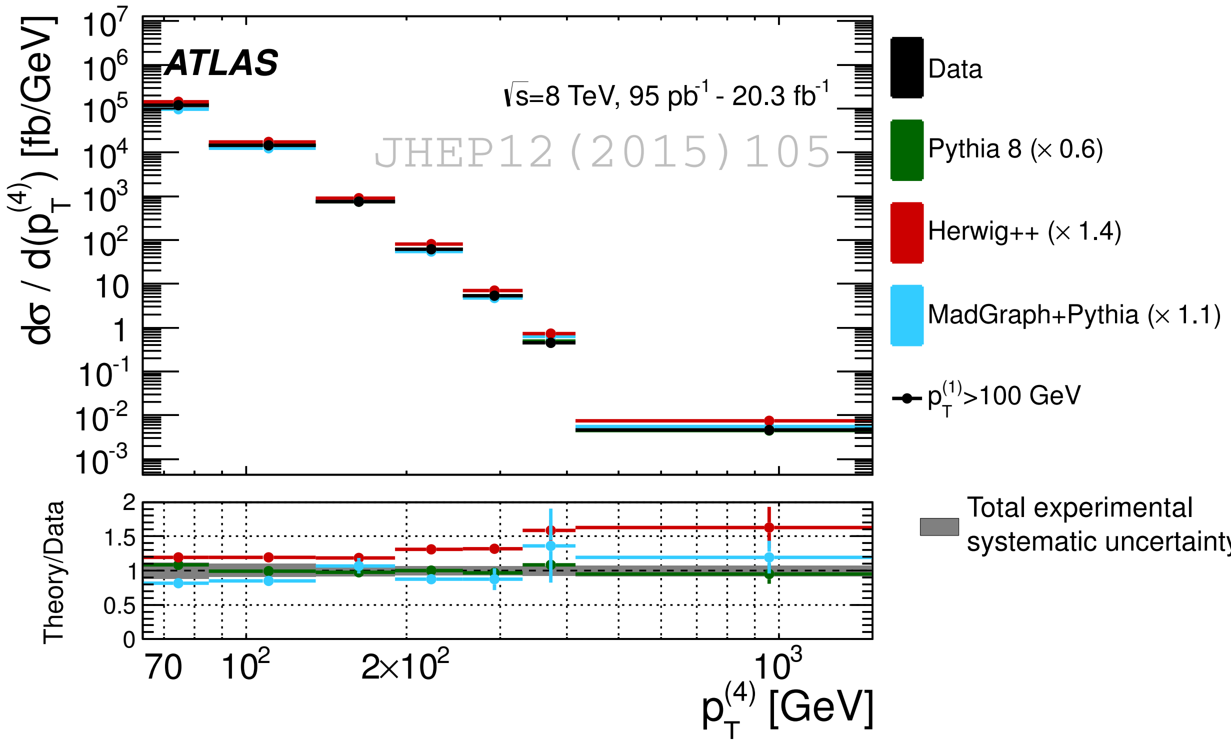
or
- requiring transverse momenta to be decreasing

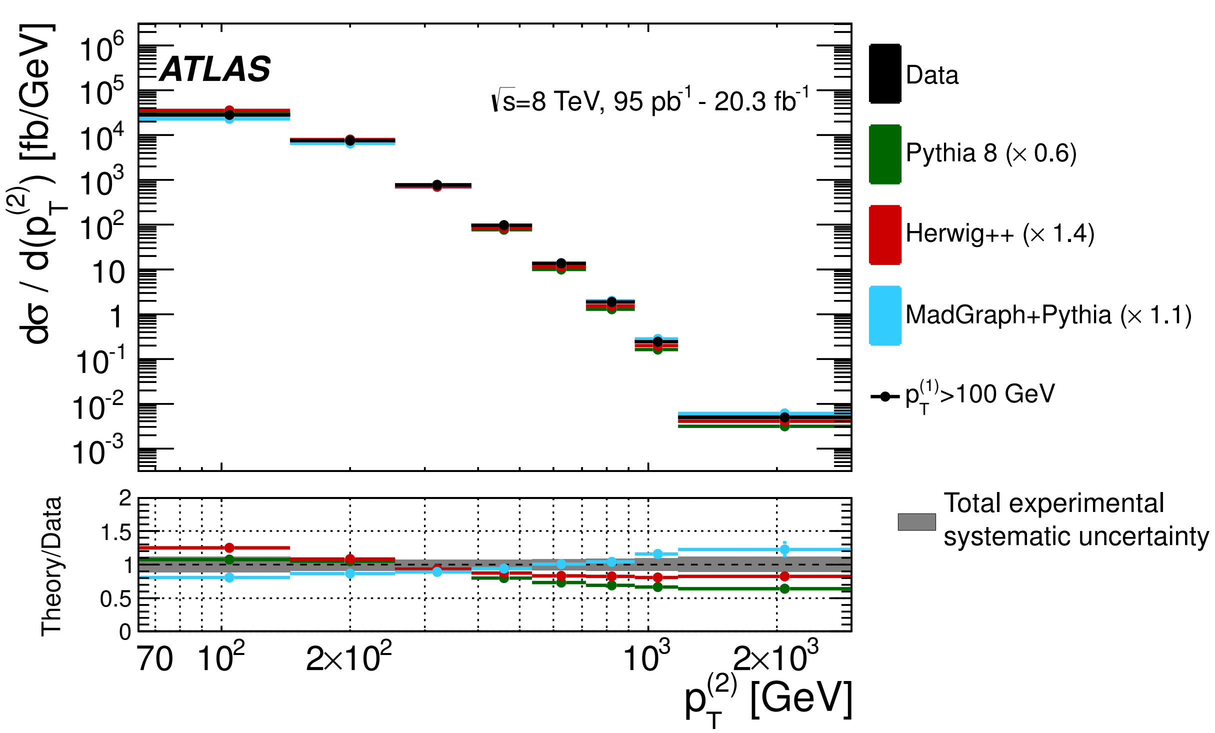
[from G.Herten]

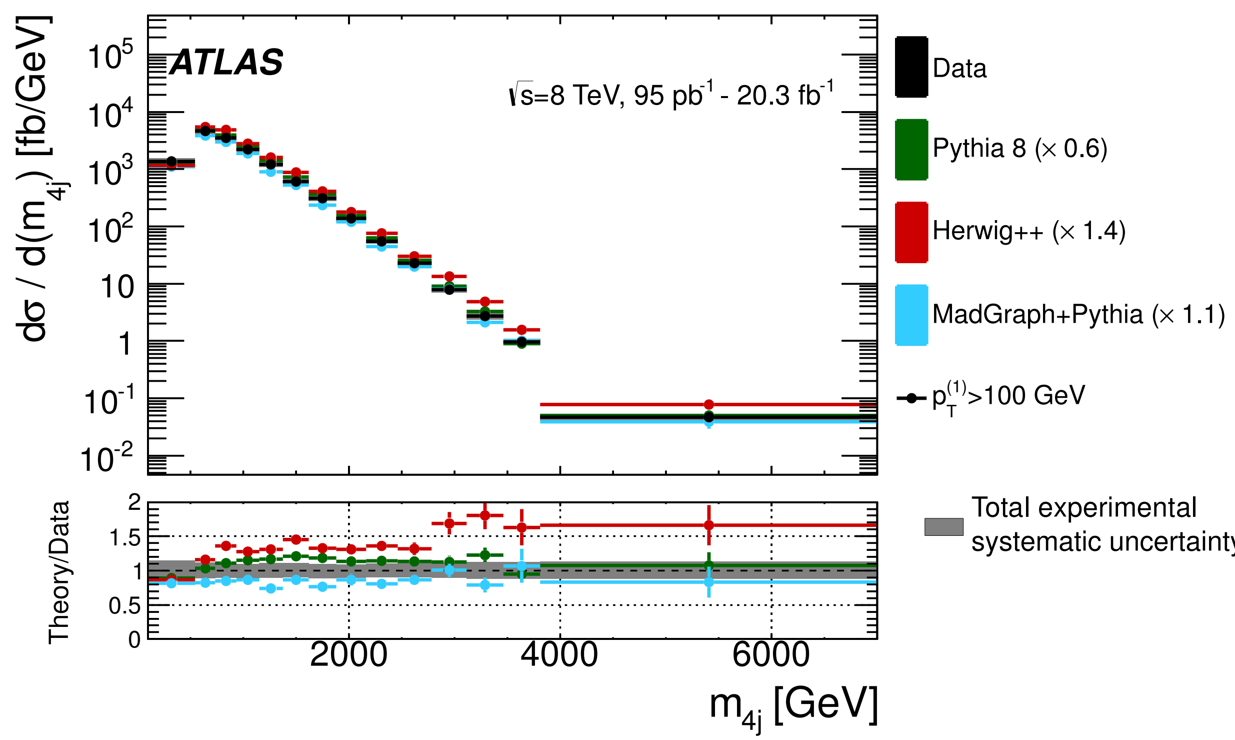
Compariosn to LHC data

4jets cross section: $p_T^{(1)} > p_T^{(2)} > p_T^{(3)} > p_T^{(4)}$









Example of processes implemented in Pythia6

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g \gamma^*_T \to f_i \bar{f}_i$
136	$g \gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}^*_\ell$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

Process simulation

Many specialized processes already available in Pythia8/Herwig++

but, processes usually only implemented in lowest non-trivial order ...

Need external programs that ...

1. include higher order loop corrections or, alternatively, do kinematic dependent rescaling

3. allow matching of higher order ME generators [otherwise need to trust parton shower description …]

5. provide correct spin correlations often absent in PS ...[e.g. top produced unpolarized, while t ➛ bW ➛ blv decay correct]

7. simulate newly available physics scenarios …[appear quickly; need for many specialised generators]

Les Houches Accord ...

Specifies how parton-level information about the hard process and sequential decays can be encoded and passed on to a general-purpose generator.

Les Houches: regular annual meeting between theoreticians and experimentalists on MC generator developments.

Specialised Generators [some examples]

Specialized Generator
[➛ Hard Process]

↓

Les Houches Interface

↓

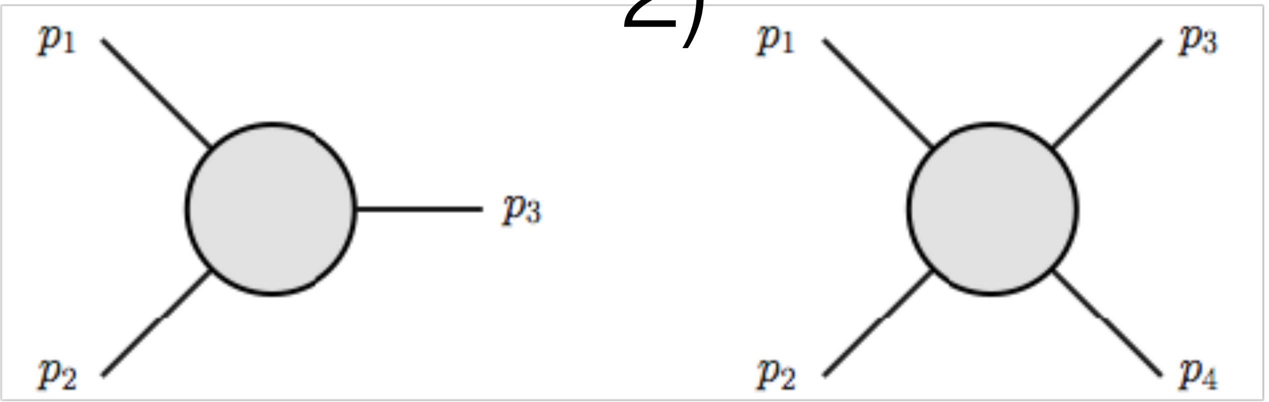
Herwig, Pythia, Herwig++/7, Pythia8
- [Resonance Decays]
- Parton Showers
- Underlying Event
- Hadronization
- Ordinary Decays

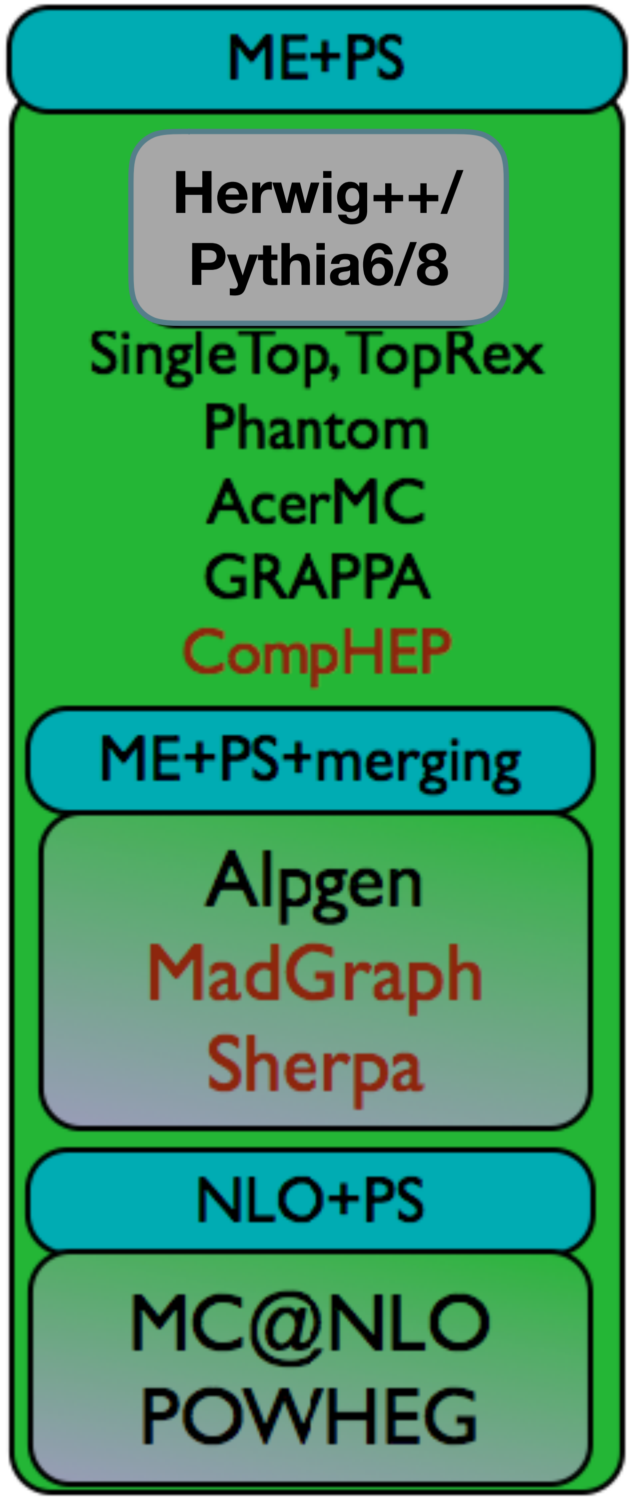
AcerMC :	ttbb, .sinlr top
ALPGEN	: W/Z + ≤ 6j, nW + mZ + kH + ≤ 3j, ...
AMEGIC++	: generic LO
CompHEP	: generic LO
GRACE [+Bases/Spring]	: generic LO [+ some NLO loops]
GR@PPA	: bbbb
MadCUP	: W/Z+ ≤ 3j, ttbb
HELAS & MadGraph	: generic LO
MCFM	: NLO W/Z+ ≤ 2j, WZ, WH, H+ ≤ 1j
O'Mega & WHIZARD	: generic LO
VECBOS	: W/Z+ ≤ 4j
HRES	: Higgs boson production @NNLO
DYNNLO	: W/Z production @NNLO

Type I : Leading order matrix element & leading log parton shower

LO ME for hard processes
[2→1 or 2→2]

1) 2)





 [F. Maltoni]

Type I : Leading order matrix element & leading log parton shower

LO ME for hard processes
[2→1 or 2→2]

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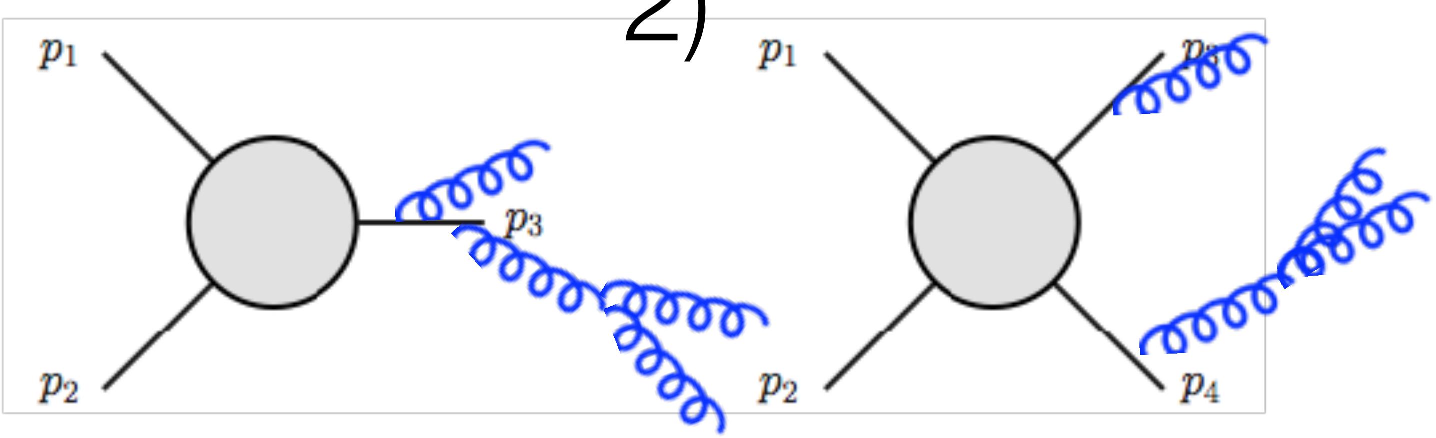
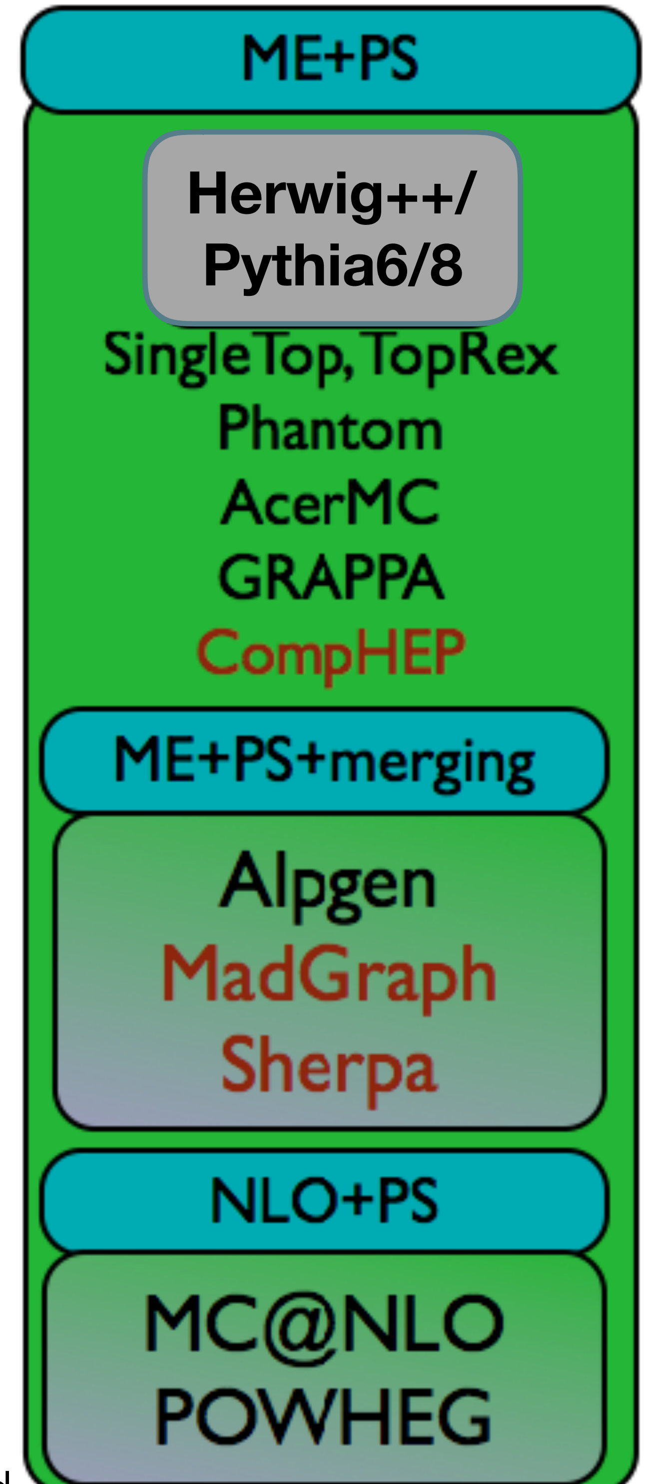


- Parton Shower: attaches gluons at each leg.
- only in soft-collinear approxmation
- typically underestimate large angle/hard emission
- 1) or 2) at ME (different generations, different accuracy: cannot be combined

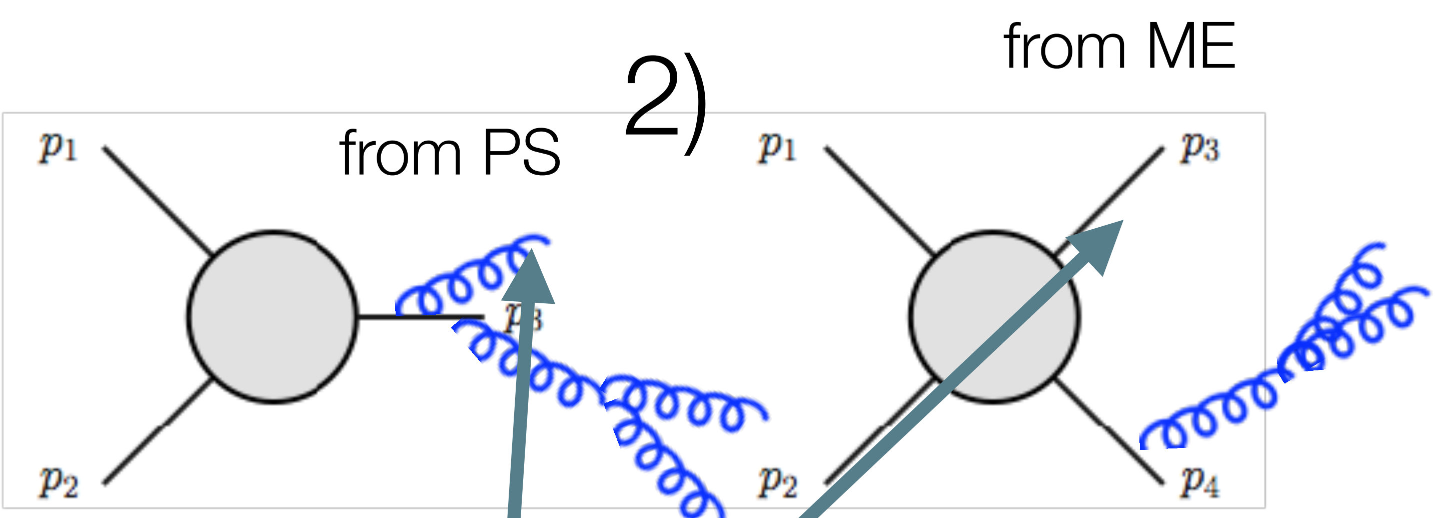


[F. Maltoni]

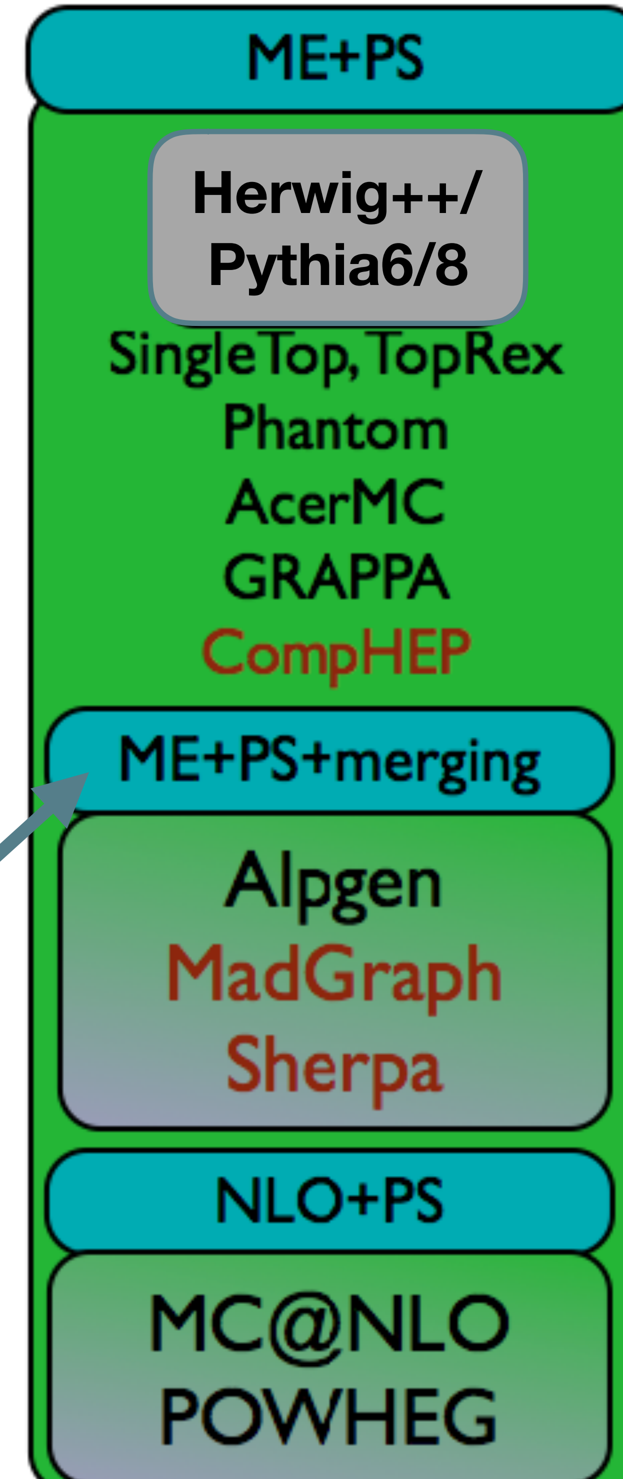
Type 2 : Leading order matrix element & leading log parton shower + merging

LO ME for hard processes
[2→1 or 2→2]

1)



- Type 1 can be improved using 1) + 2)
- use ME calculation for hard/large angle jets
- but needs to remove double-counting: merging (CKKW, MLM)
- very good description of high jet multiplicity kinematics



Merging @LO

MLM matching (simplified)

1) define matching cuts:
for example $p_T^J > 20$ GeV, $\Delta R=0.4$

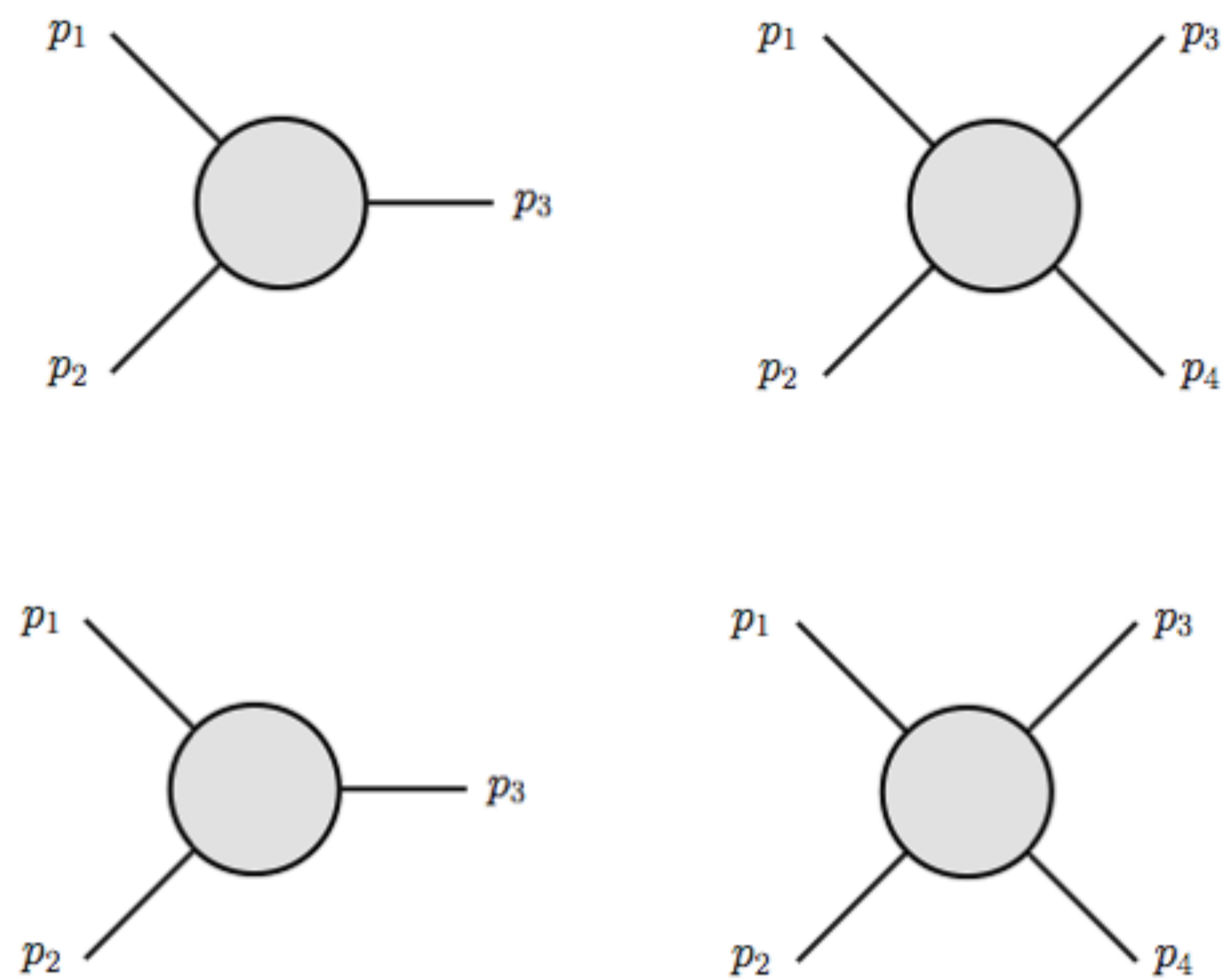
Merging @LO

MLM matching (simplified)

1) define matching cuts:
for example p_T^J > 20 GeV, ΔR=0.4

2) generate ME with 1, 2, …n jets

1 parton   2 partons



Merging @LO

MLM matching (simplified)

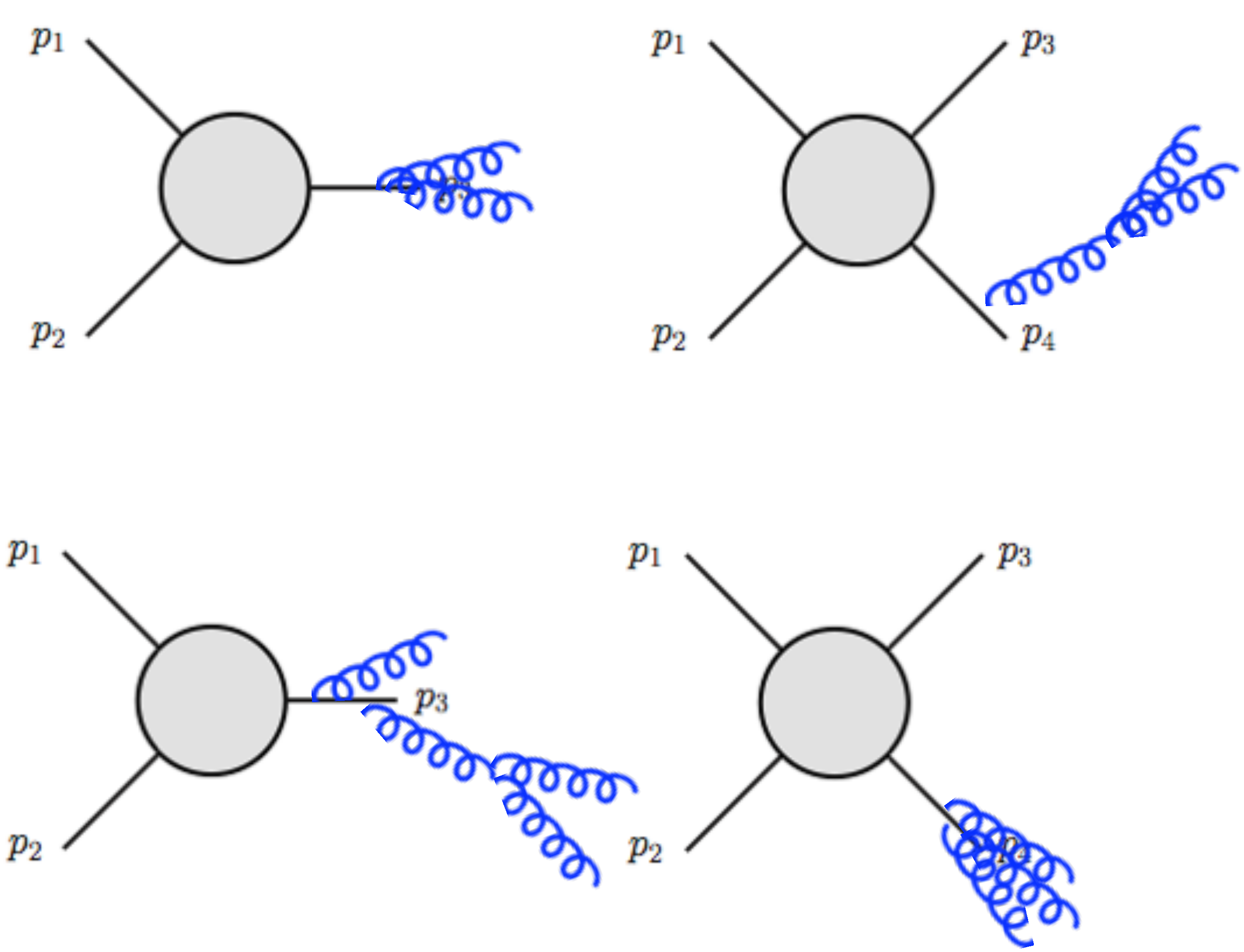
1) define matching cuts:
for example p_T^J > 20 GeV, ΔR=0.4

2) generate ME with 1, 2, …n jets

3) shower all events

1 parton

2 partons



Merging @LO

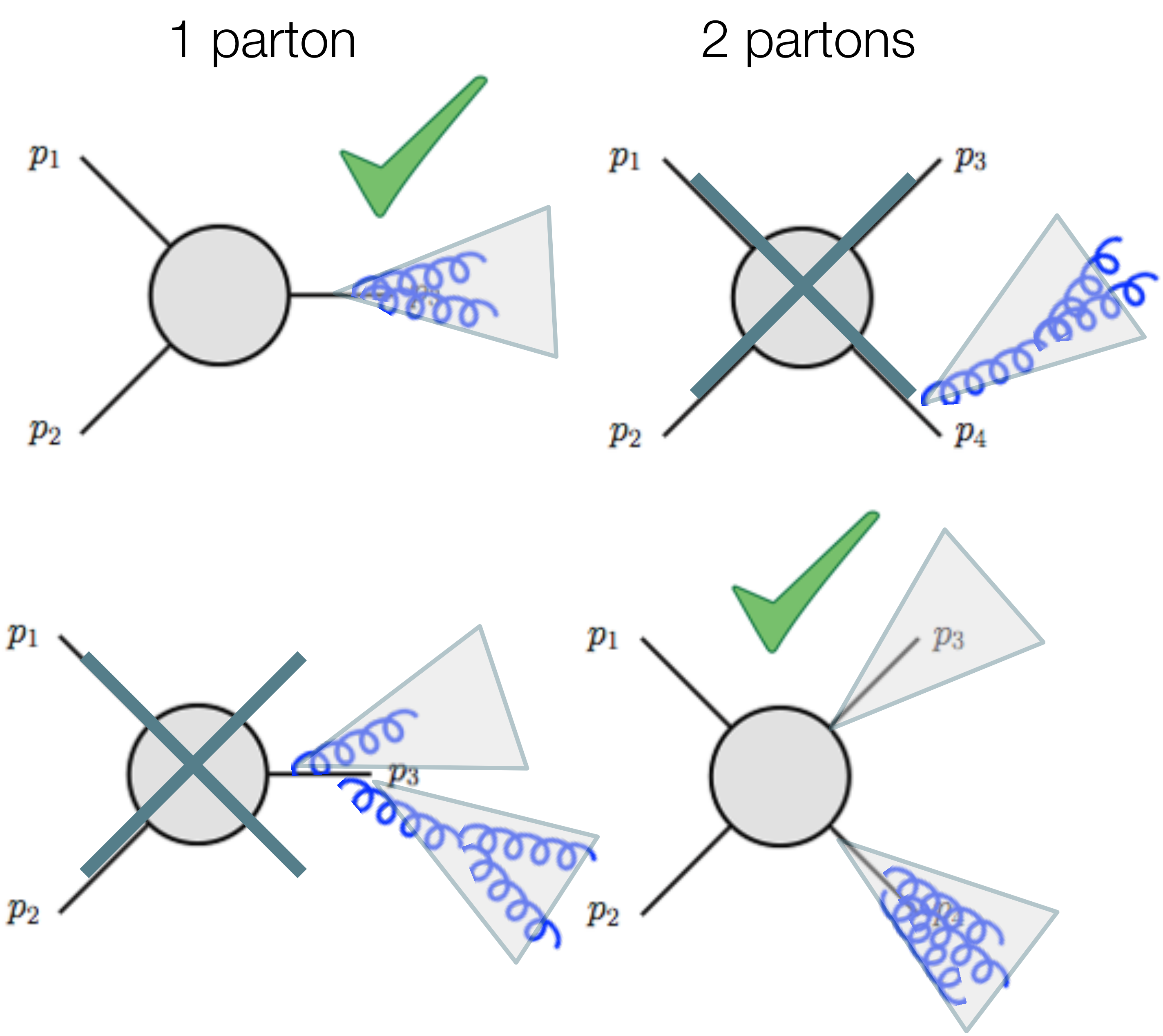
MLM matching (simplified)

1) define matching cuts:
for example $p_T^J > 20$ GeV, $\Delta R=0.4$

2) generate ME with 1, 2, …n jets

3) shower all events

4) select only events where jets above the p_T threshold match with final partons



Merging @LO

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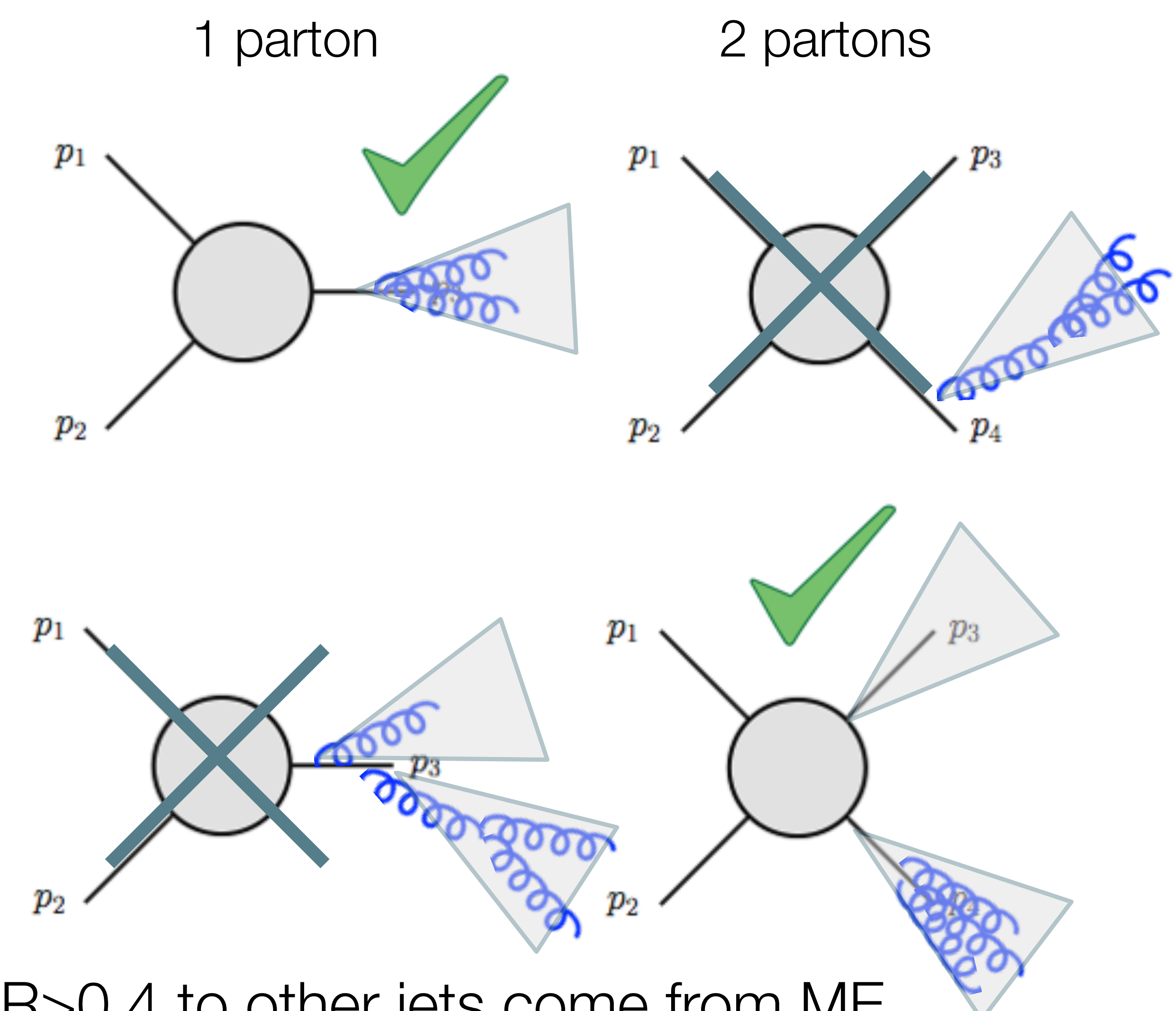
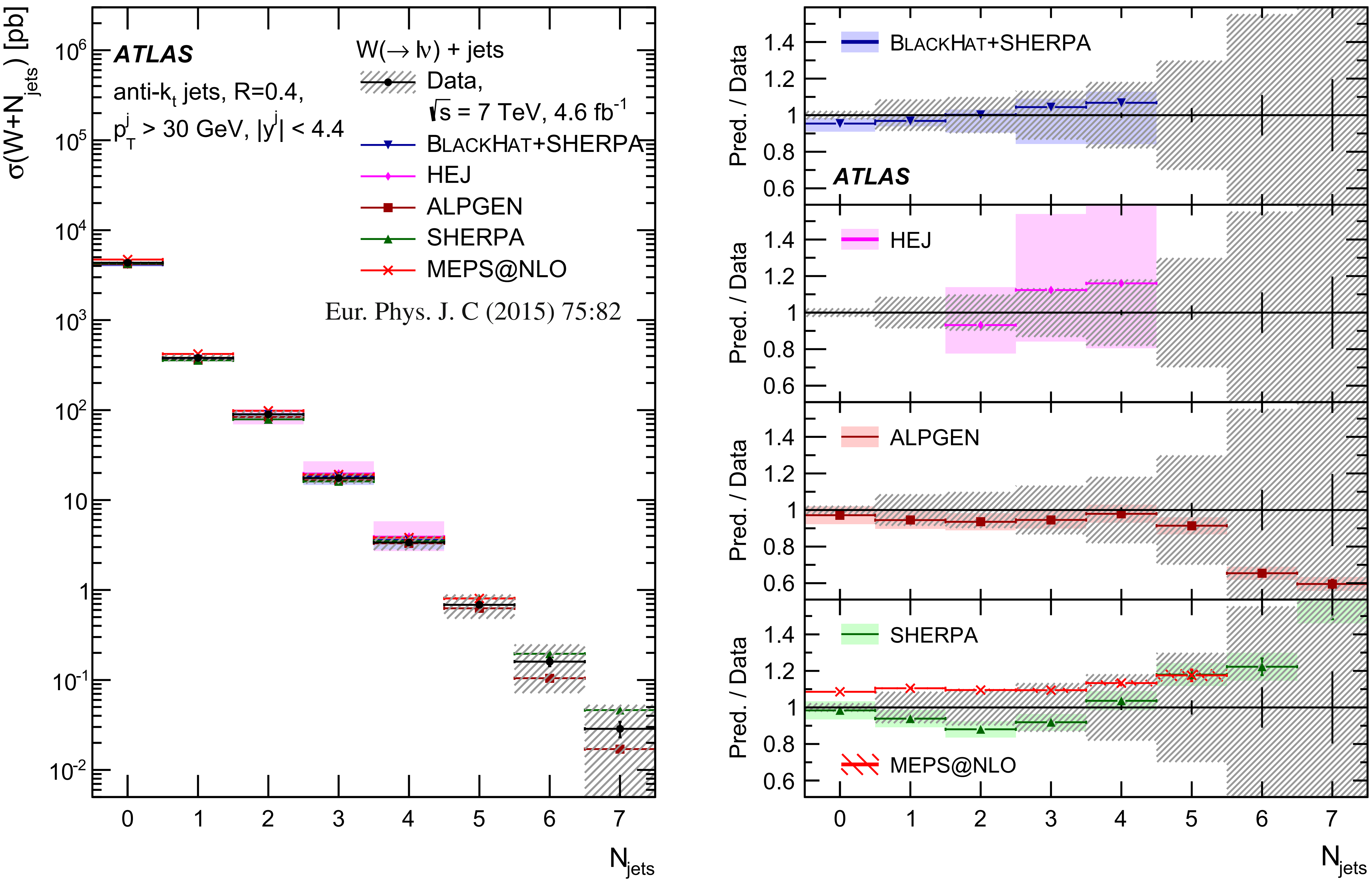


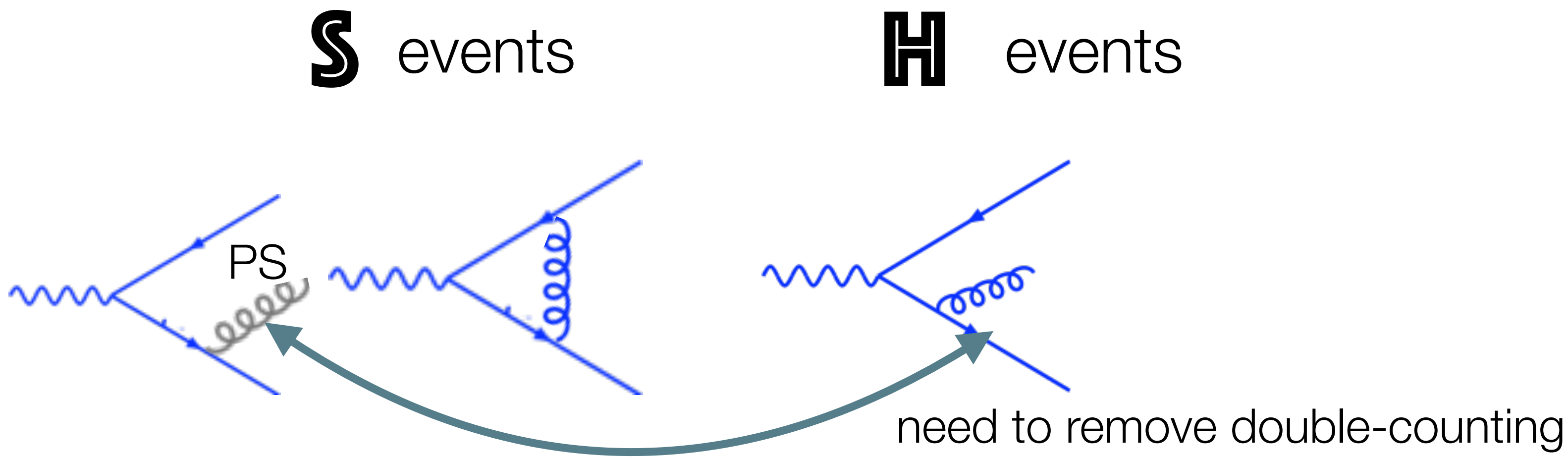
Consequences:

all jets with $p_T > 20$ GeV and $\Delta R>0.4$ to other jets come from ME
collinear and soft jets come from PS
Use each of them where they are best.

W+jets distributions

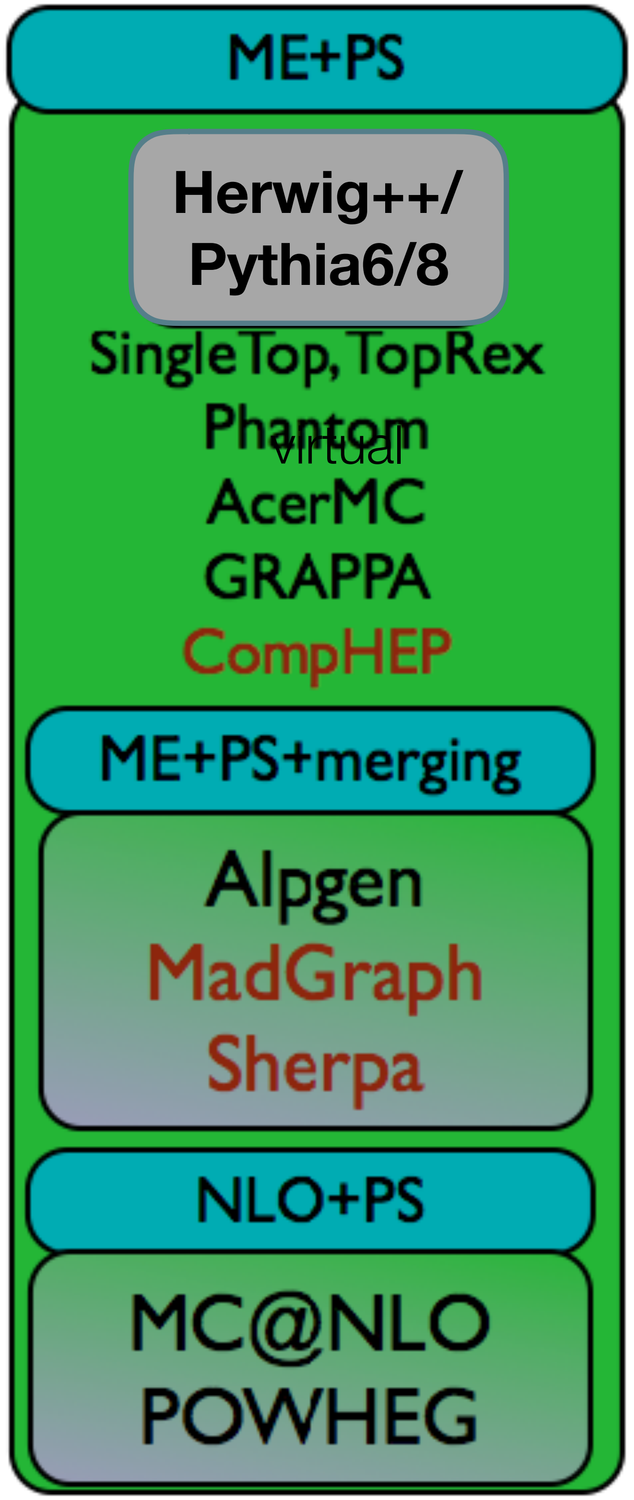


Type III : Next-to-leading order ME & leading-log parton shower



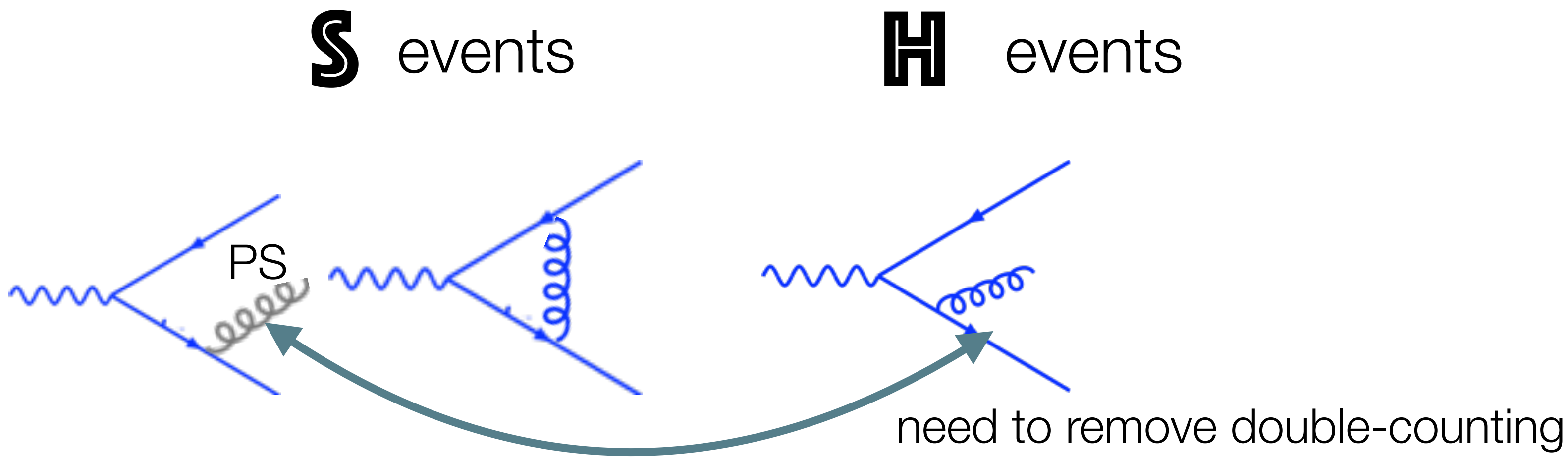
hard processes simulated at NLO accuracy including real & virtual corrections ...

improved description of cross sections & kinematic distributions



[F. Maltoni]

Type III : Next-to-leading order ME & leading-log parton shower



hard processes simulated at NLO accuracy including real & virtual corrections ...

improved description of cross sections & kinematic distributions

2 Matching methods:

1. Powheg

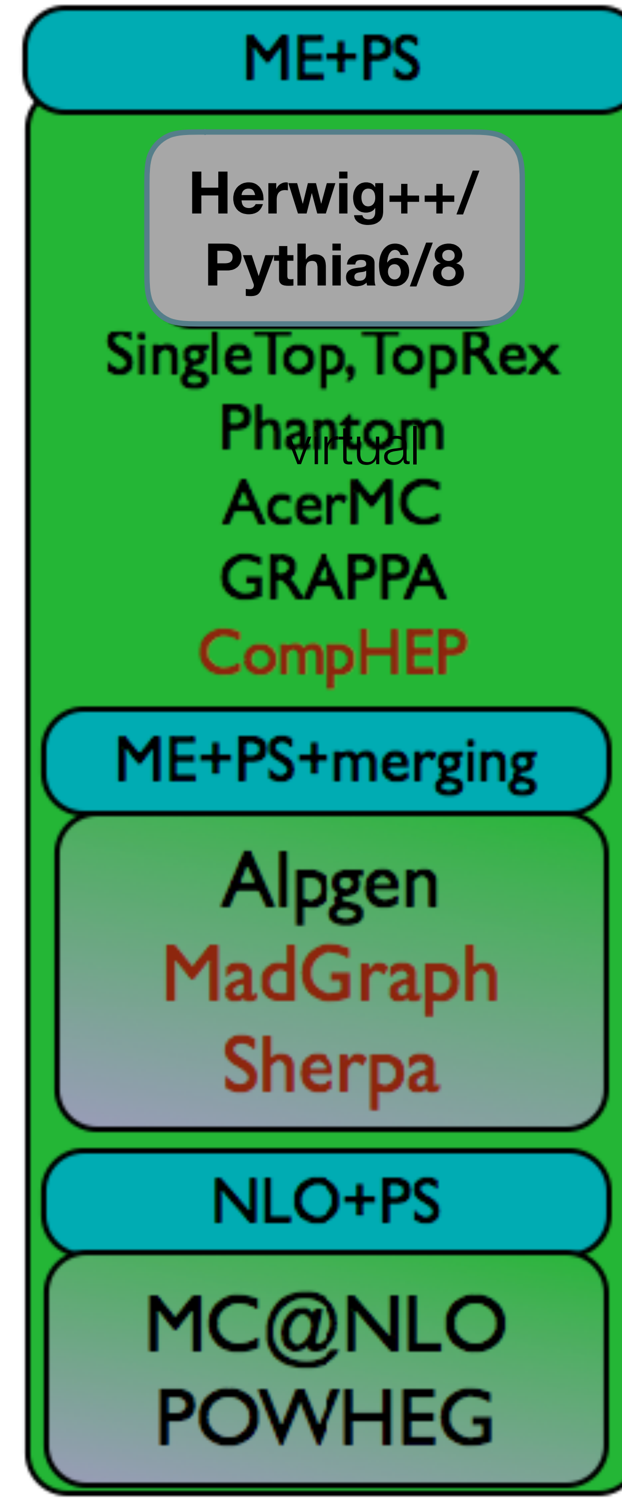
Truncated showers:

1) first emission produced by the ME;
2) don’t allow the PS to produce patrons harder than the first emission;
3) not exact at NLO (containes unbalanced higher order terms)

2. MC@NLO:

$$|ME|^2 = |ME + PS - PS(\text{up to } \alpha_s^2)|^2$$

+ Result is exact at NLO…
- produce some negative weights, need retuning for each PS



[F. Maltoni]

Merging @NLO (quite new, going to be used at 13 TeV)

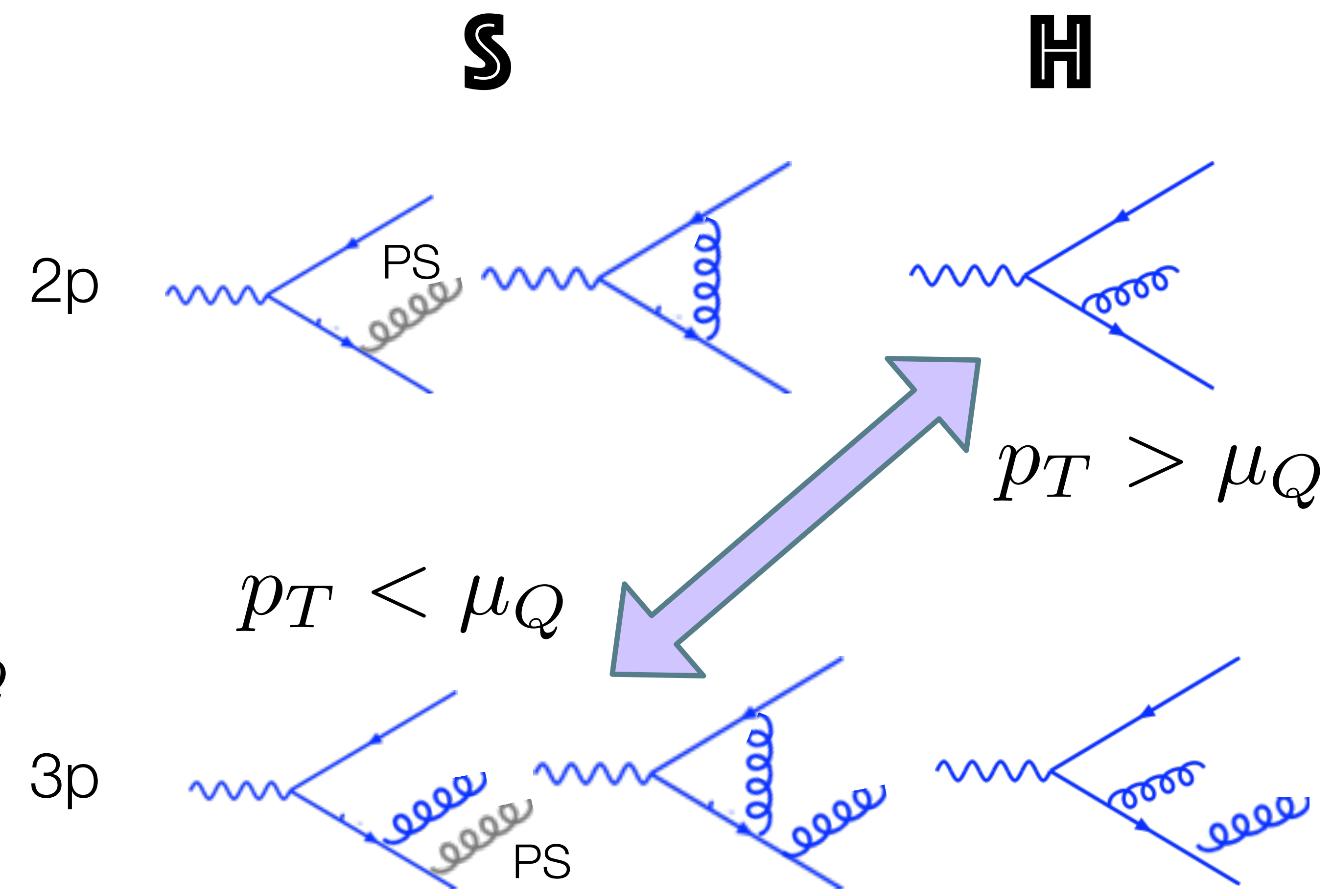
JHEP12(2012)061

FxFx (Frederix-Frixione) merging

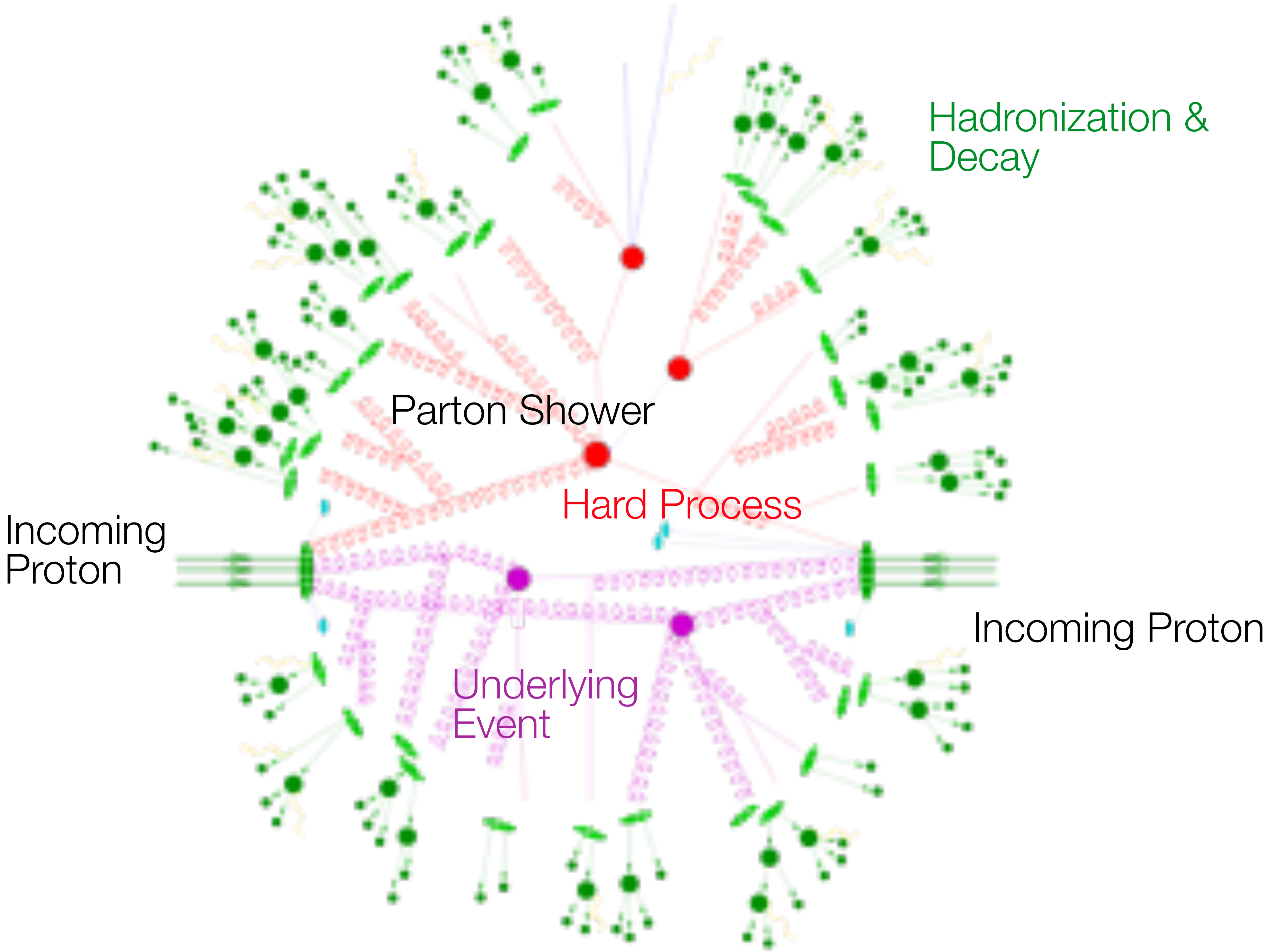
1) define a matching scale μ_Q;

2) don't allow 𝕊 events with $p_T > \mu_Q$ (those will be provided by ℍ events of n-1 partons NLO real emission); the restriction is imposed both at ME and on the shower starting scale $\mu < \mu_Q$

3) treat the obtained events as LO ones and apply an LO-style merging (this allow to produce smoother distributions)



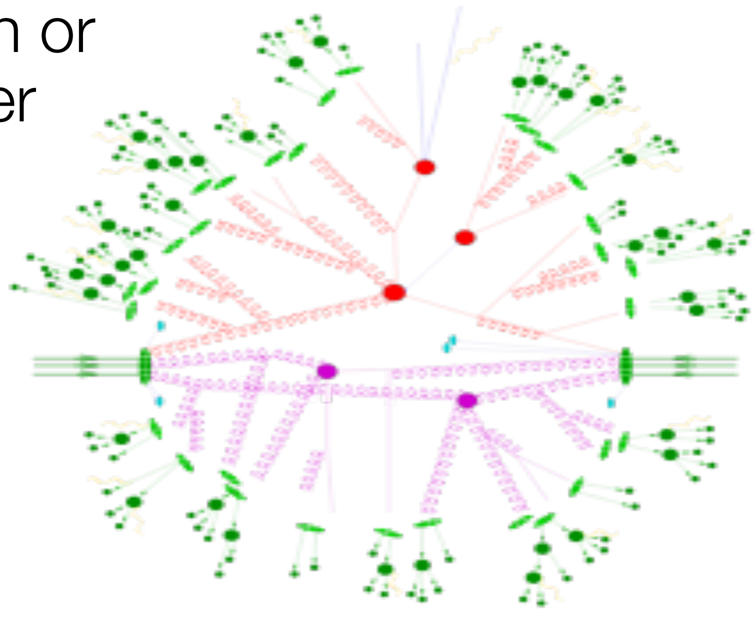
Let’s recap



[T. Gleisberg et al., JHEP02 (2004) 056]

From partons to color neutral hadrons

Fragmentation or
Parton Shower



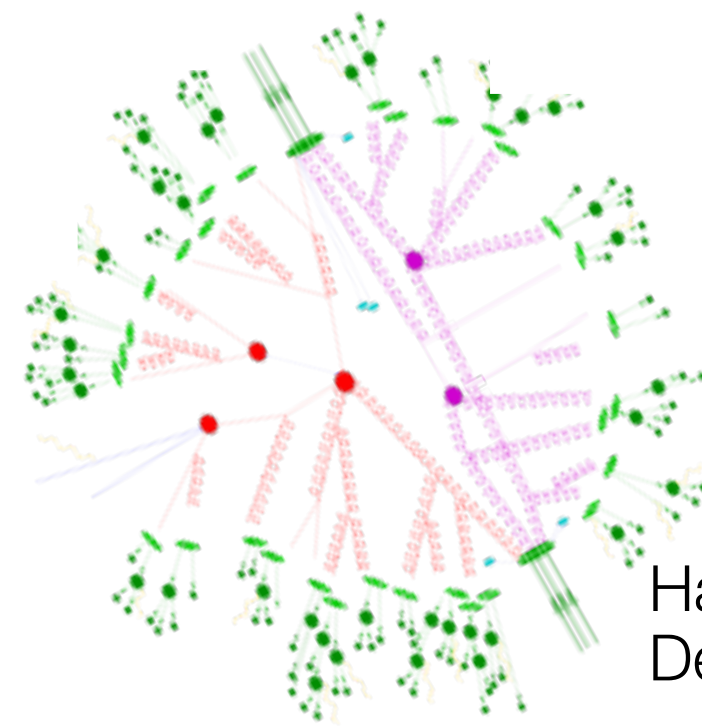
Fragmentation:

Parton splitting into other partons
[QCD: re-summation of leading-logs]
["Parton shower"]

Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]



Hadronization &
Decays

Non-perturbative transition from partons to hadrons ...

[Modelling relies on phenomenological models available]

Models based on MC simulations very successful:

Generation of complete final states ...
[Needed by experimentalists in detector simulation]

Caveat: tunable ad-hoc parameters

Most popular MC models:

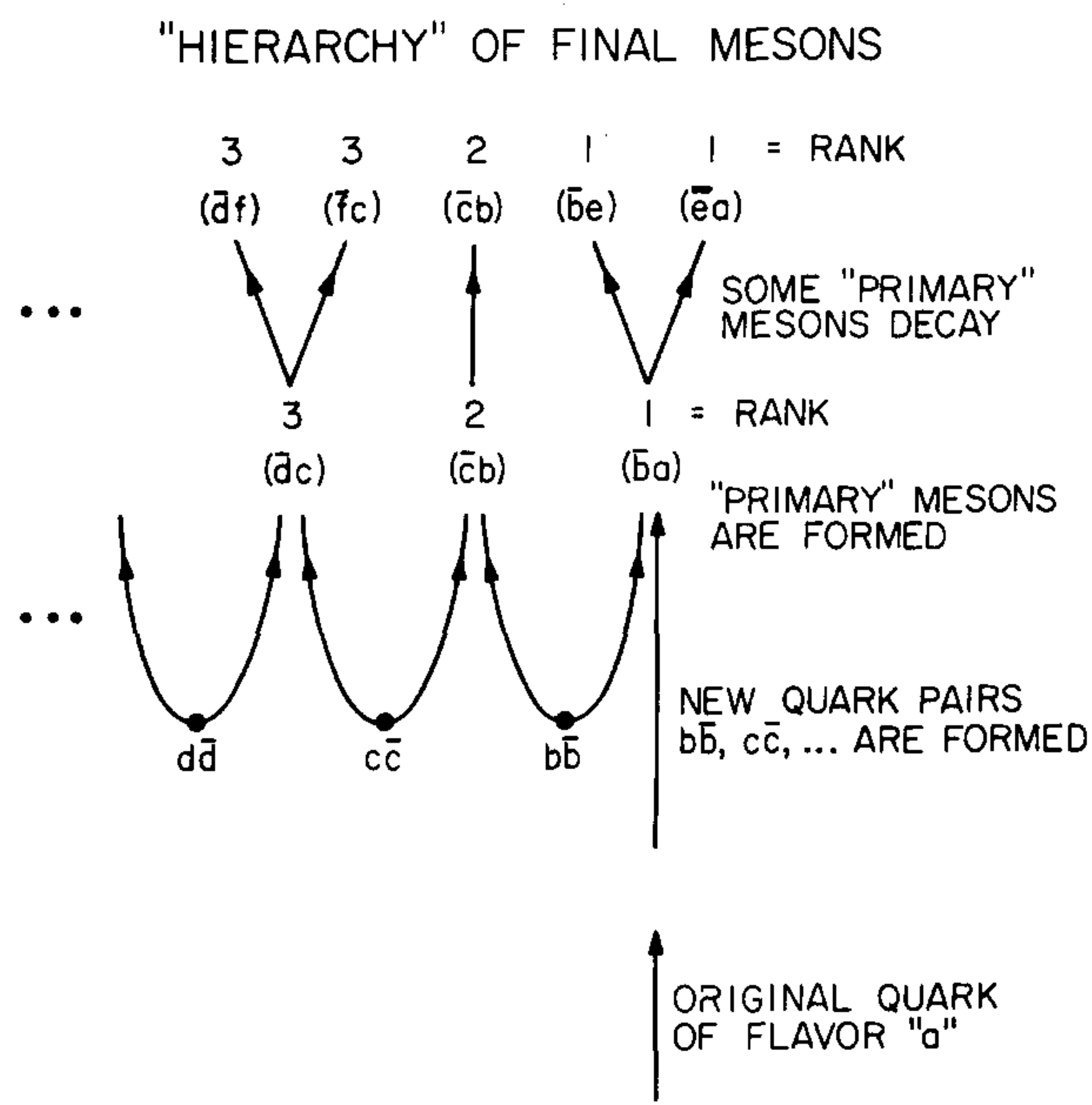
Pythia/8 : Lund string model
Herwig/++ : Cluster model

Independent fragmentation of each parton

Simplest approach:
[Field, Feynman, Nucl. Phys. B136 (1978) 1]

- Start with original quark
- Generate quark-antiquark pairs from vacuum
  - ➛ form "primary meson" with energy fraction z
- Continue with leftover quark with energy fraction 1–z
- Stop at low energies (cut-off)
- Include flavour non-perturbative fragmentation functions D(z)

D(z): probability to find a meson/hadror with energy fraction z in jet ...

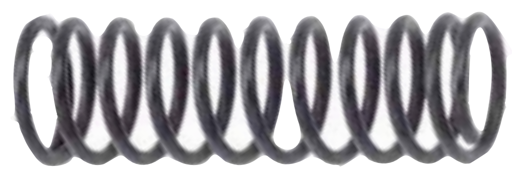


Lund String Model

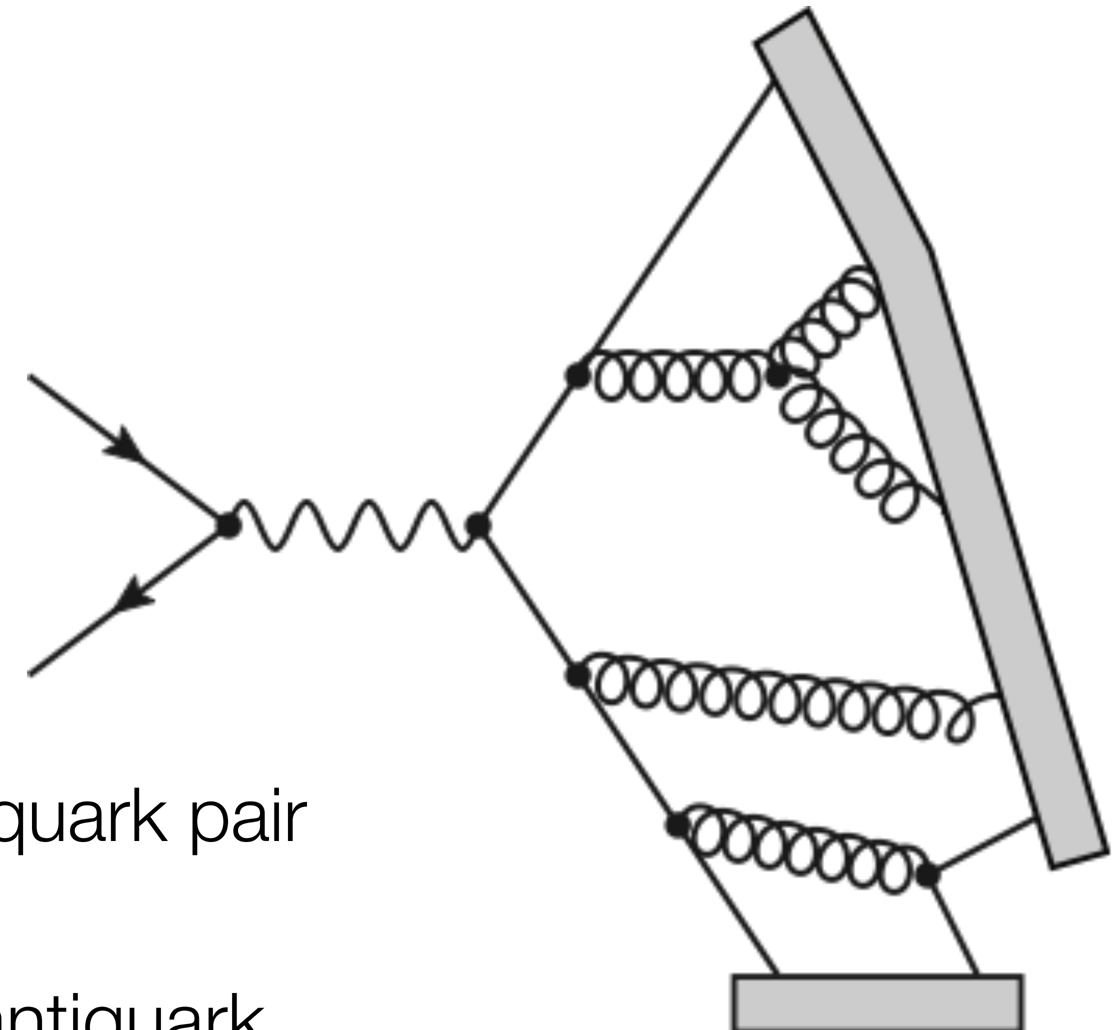
[Andersson et al., Phys. Rep. 97 (1983) 31]

QCD potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(1/r^2)}{r} + kr$$



neglected



After: Ellis et al.,
QCD and Collider Physics

String formation between initial quark-antiquark pair

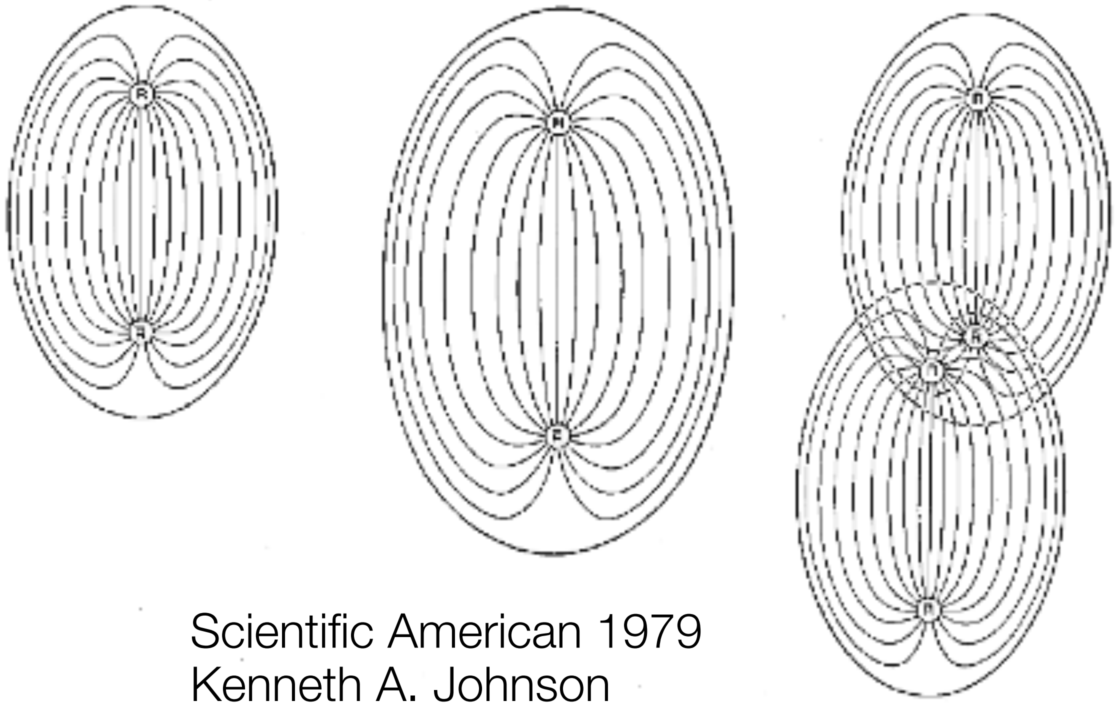
- String breaks up if potential energy large enough to produce a new quark-antiquark pair
- Gluons = 'kinks' in string
- At low energy: hadron formation
- Very widely used ...
  [default in Pythia 6/8]

Lund String Model

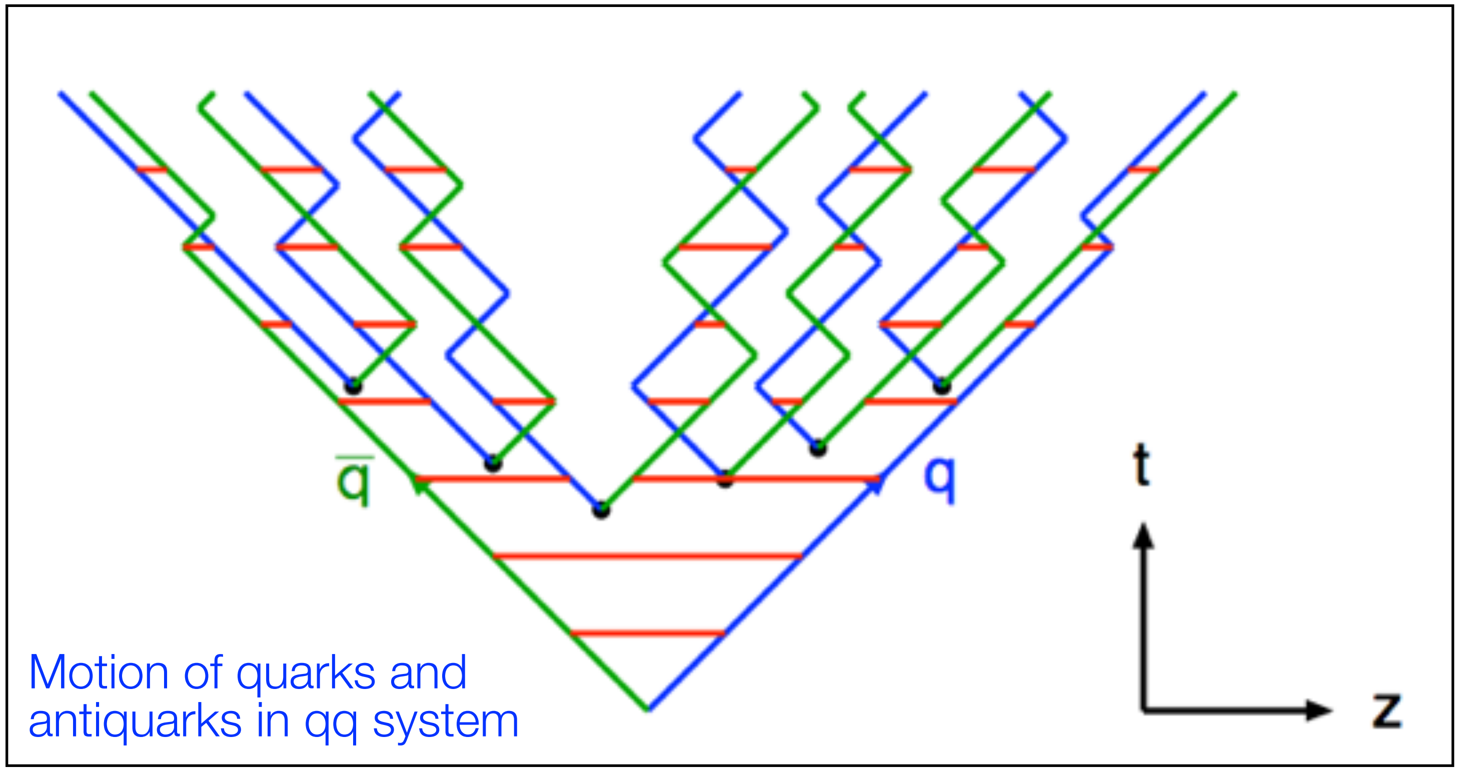
Repeated string breaks for large system with pure V(r) = κ·r, i.e. neglect Coulomb part

$$\left|\frac{dE}{dz}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dp_z}{dt}\right| = \kappa$$

Energy-momentum quantities can be read from space-time quantities ...



Scientific American 1979
Kenneth A. Johnson



Simple but powerful picture of hadron production

[with extensions to massive quarks, baryons, ...]

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right)$$

$$\propto \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

Yields: Common Gaussian p⊥ spectrum
Heavy quark suppression

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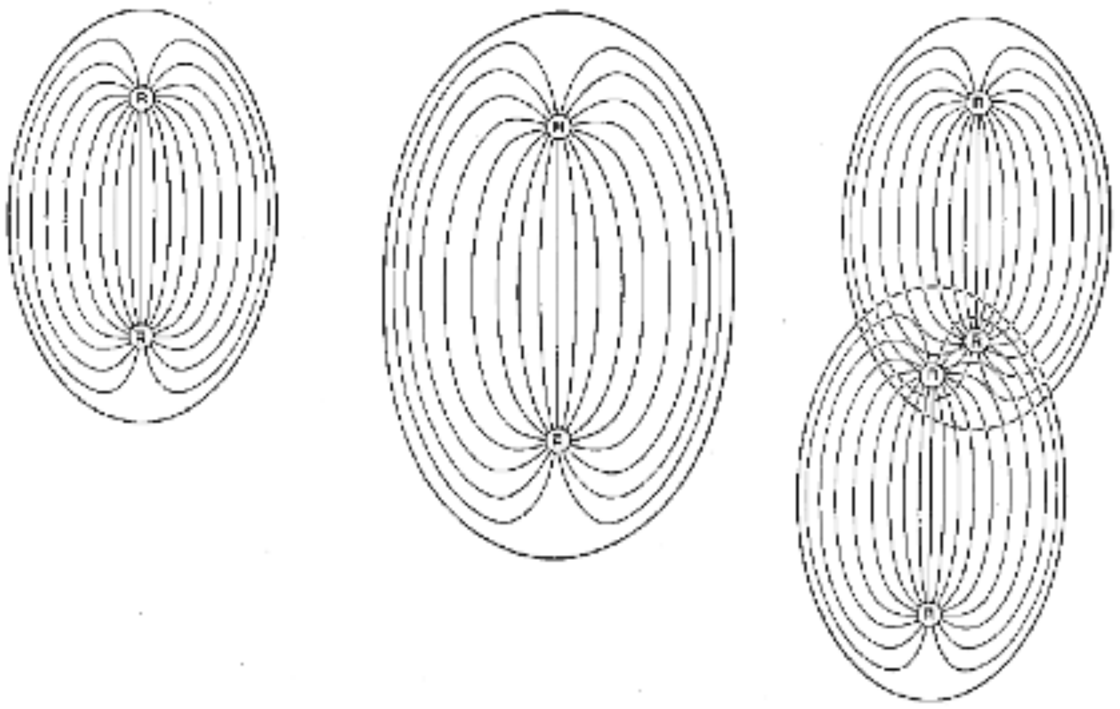

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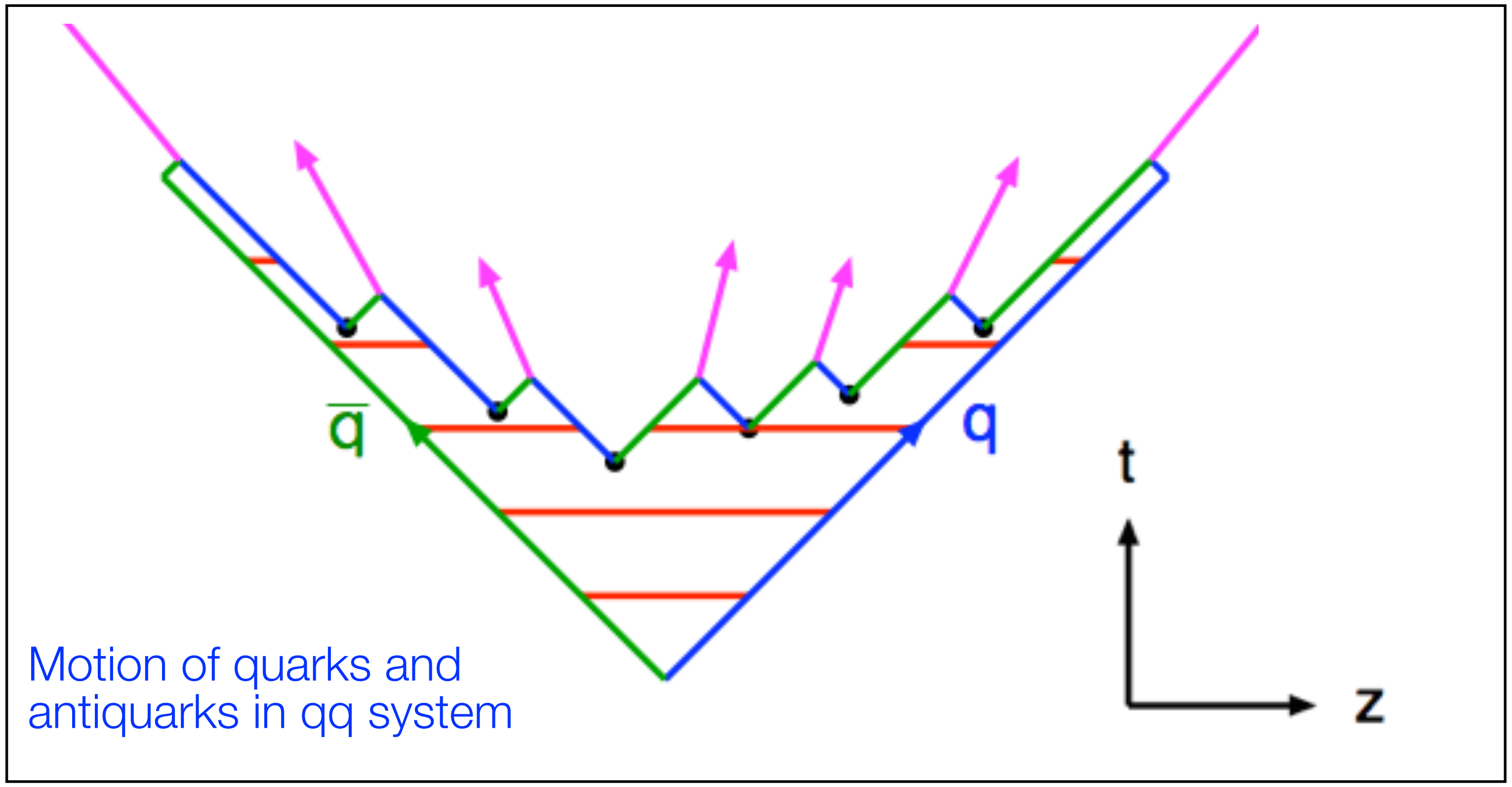

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Yields: Common Gaussian p⊥ spectrum
Heavy quark suppression

Cluster Model

[Webber, Nucl. Phys. B238 (1984) 492]

Color flow confined during hadronisation process

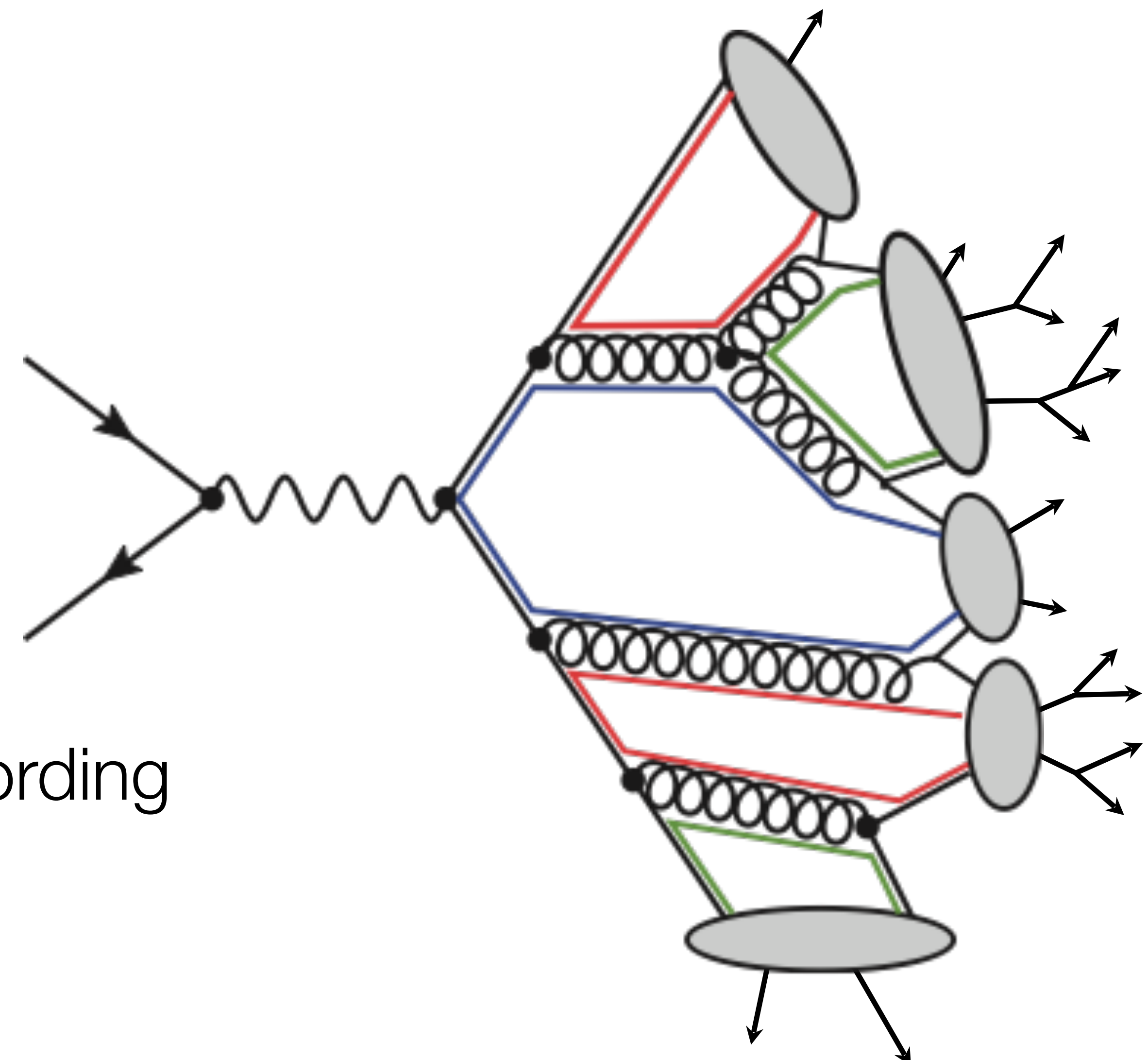
➛ Formation of color-neutral parton clusters

Gluons (color-anticolor) split to quark-antiquark pairs

Clusters decay into 2 hadrons according to phase-space, i.e. isotropically

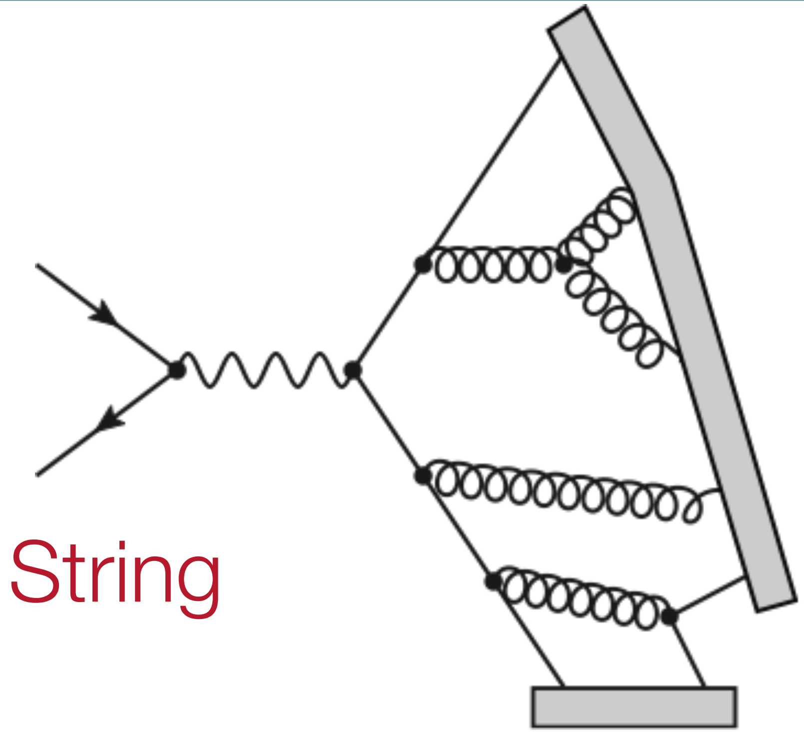
➛ no free tuning parameters parton clusters

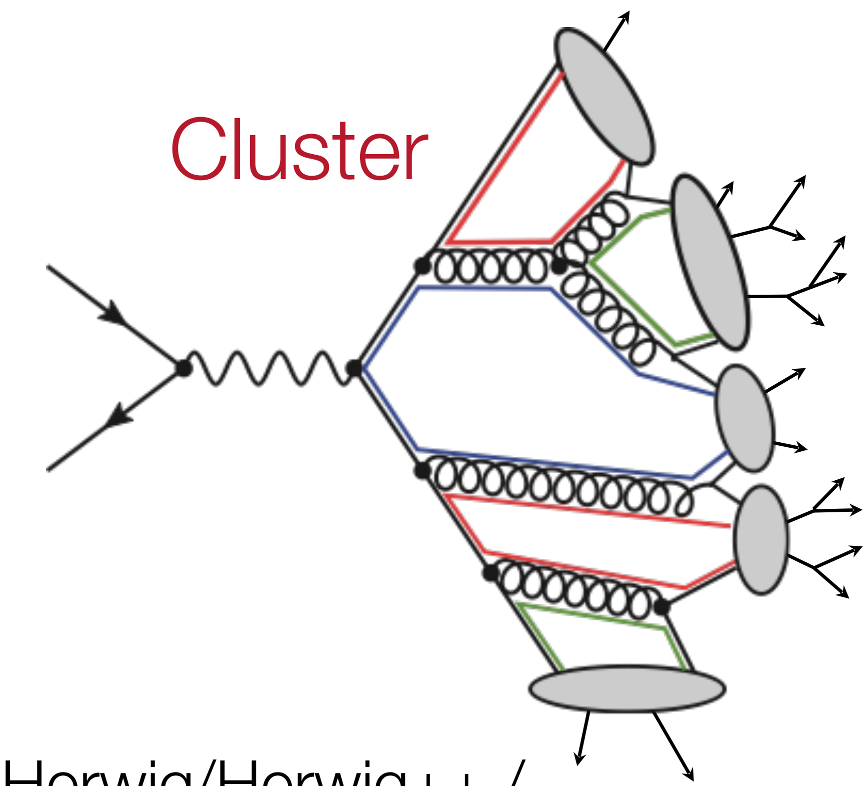
Very widely used ...
[default in Herwig/Herwig++]



After: Ellis et al.,
QCD and Collider Physics

Hadronisation models summary





Model	Pythia6/8 (string)	Herwig/Herwig++ / Sherpa(cluster)
Energy-mom. picture	powerful	simple
	predictive	unpredictive
Parameters	few	many
Flavour composition	messy	simple
	unpredictive	in-between
Parameters	many	few

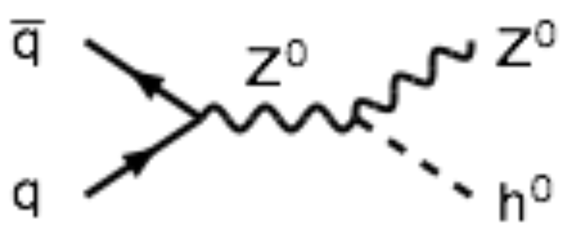
[from G.Herten,T.Sjöstrand]

Structure of basic generator process [by order of consideration]

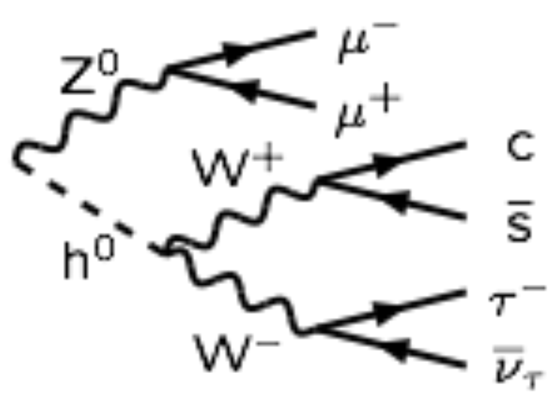
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modelled; at small

Matrix elements (ME)

1. Hard subprocess:
   $|M|^2$, Breit Wigners, PDFs

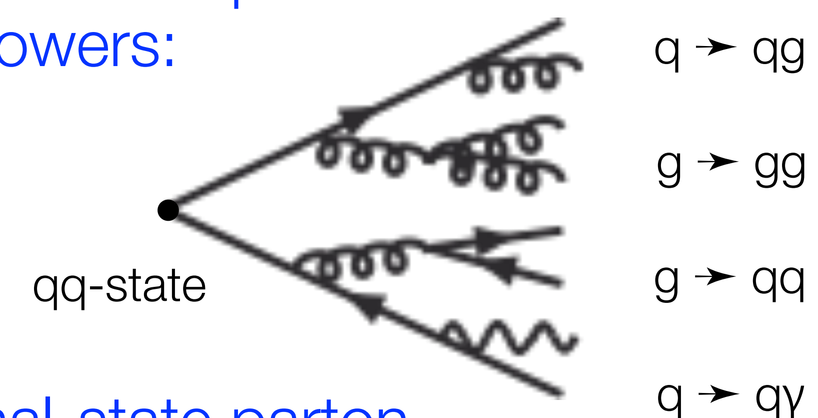


2. Resonance decays:
   Includes particle correlations

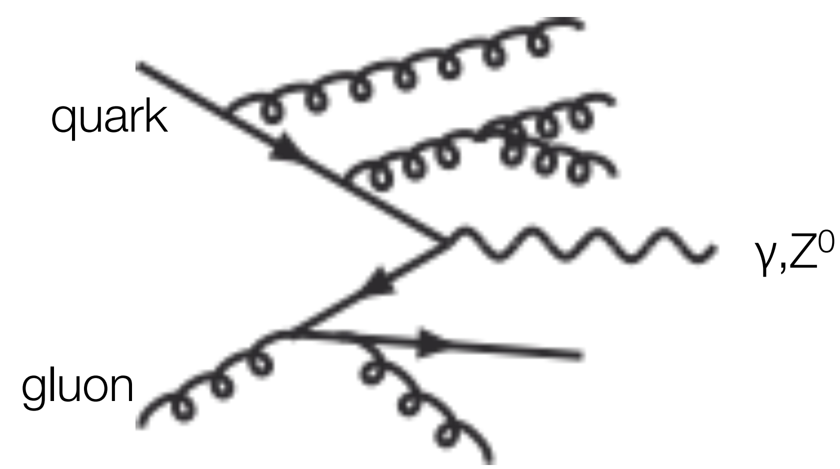


Parton Shower (PS)

3. Final-state parton
   showers:



4. Final-state parton
   showers:



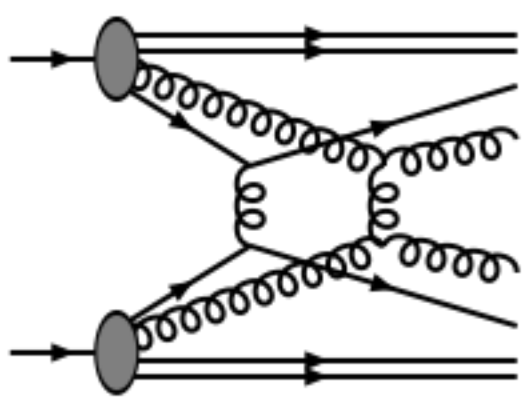
[from G.Herten]

Conclusions: Structure of basic generator process

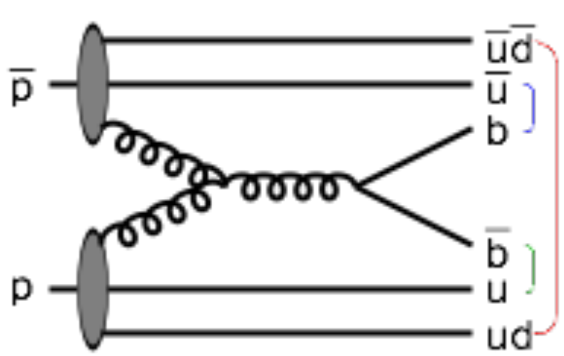
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modelled; at small

Underlying Event (UE)

5. Multi-parton interaction:

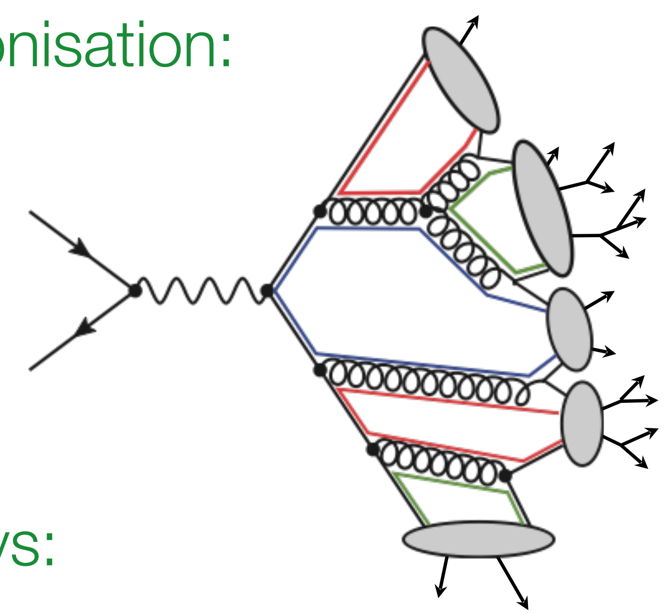


6. Beam remnants:

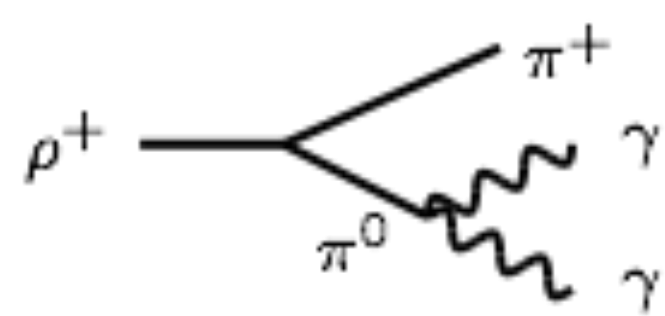


Stable Particle State

7. Hadronisation:



8. Decays:



[from G.Herten]

The DGLAP evolution equation is said to resum large collinear logarithms. So where are these logarithsm, and where is the resummation?

Let's perform the integration of the DGLAP equation and expand the result:

$$
\begin{aligned}
f(x,t) &= f_0(x) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\alpha_s(t')}{2\pi} \int_x^1 \frac{dz}{z} P(z)\, q\left(\frac{x}{z}, t'\right) \\
&= f_0(x) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} P(z) \left\{ f_0\left(\frac{x}{z}\right) + \right. \\
&\qquad \left. + \int_{t_0}^{t'} \frac{dt''}{t''} \frac{\alpha_s}{2\pi} \int_{x/z}^1 \frac{dz'}{z'} P(z') \left[f_0\left(\frac{x}{zz'}\right) + \ldots \right] \right\} \\
&= f_0(x) + \frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right) \int_x^1 \frac{dz}{z} P(z)\, f_0\left(\frac{x}{z}\right) + \\
&\qquad + \frac{1}{2!} \left[\frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right)\right]^2 \int_x^1 \frac{dz}{z} P(z) \int_{x/z}^1 \frac{dz'}{z'} P(z')\, f_0\left(\frac{x}{zz'}\right) + \ldots
\end{aligned}
$$

As suggested by the last step, it is indeed a resummation of all terms proportional to $\left[\frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right)\right]^n$.

[from J.Alwall]