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Our milestones:

1. Why do ATLAS and CMS look like they look like today?
2. **Tools used in the analyses**
3. Some highlights, and comments
4. What next?

Our Master Equation

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Event rates (absolute, relative, differential)
Stat vs syst errors, backgrounds from data or MC?
Resolution, Energy Scale, Signal Significance

$$\sigma_{meas} = \frac{N_{obs} - N_{bkg}}{\varepsilon \ L}$$

Proton-Proton Luminosity uncertainty a few %; eliminated in ratios

Experimental issues : Triggers, reconstruction, isolation cuts, low-p_T jets (jet veto) acceptance, efficiency determination

Theoretical issues : p_T distributions at N^nLO + resummation; differential calculations for detectable acceptance.

$$\sigma_{theo} = PDF(x_1, x_2, Q^2) \otimes \hat{\sigma}_{hard}$$

constrain, define uncertainties

HO calculations, implemented in MC?

Goal : test SM (in)consistency : $\sigma_{exp} \pm \Delta_{exp} \stackrel{?}{=} \sigma_{SM} \pm \Delta_{th}$

Efficiencies and Acceptance

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon L}$$

Efficiencies and acceptances

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$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \quad L}$$

$$= \epsilon_{\text{ID}} \cdot \epsilon_{\text{RECO}} \cdot \epsilon_{\text{TRIG}} \cdot A$$

Identification eff.

$$\frac{\text{Number of “reconstructed” objects/events, which have passed the ID criteria}}{\text{Number of “all reconstructed” objects/events}}$$

Trigger eff.

$$\frac{\text{Number of “detectable” objects/events, which have been triggered on}}{\text{Number of “all detectable” objects/events}}$$

Reconstruction eff.

$$\frac{\text{Number of “detectable, triggered” objects/events, which have been reconstructed}}{\text{Number of “detectable/triggered” objects/events}}$$

Acceptance

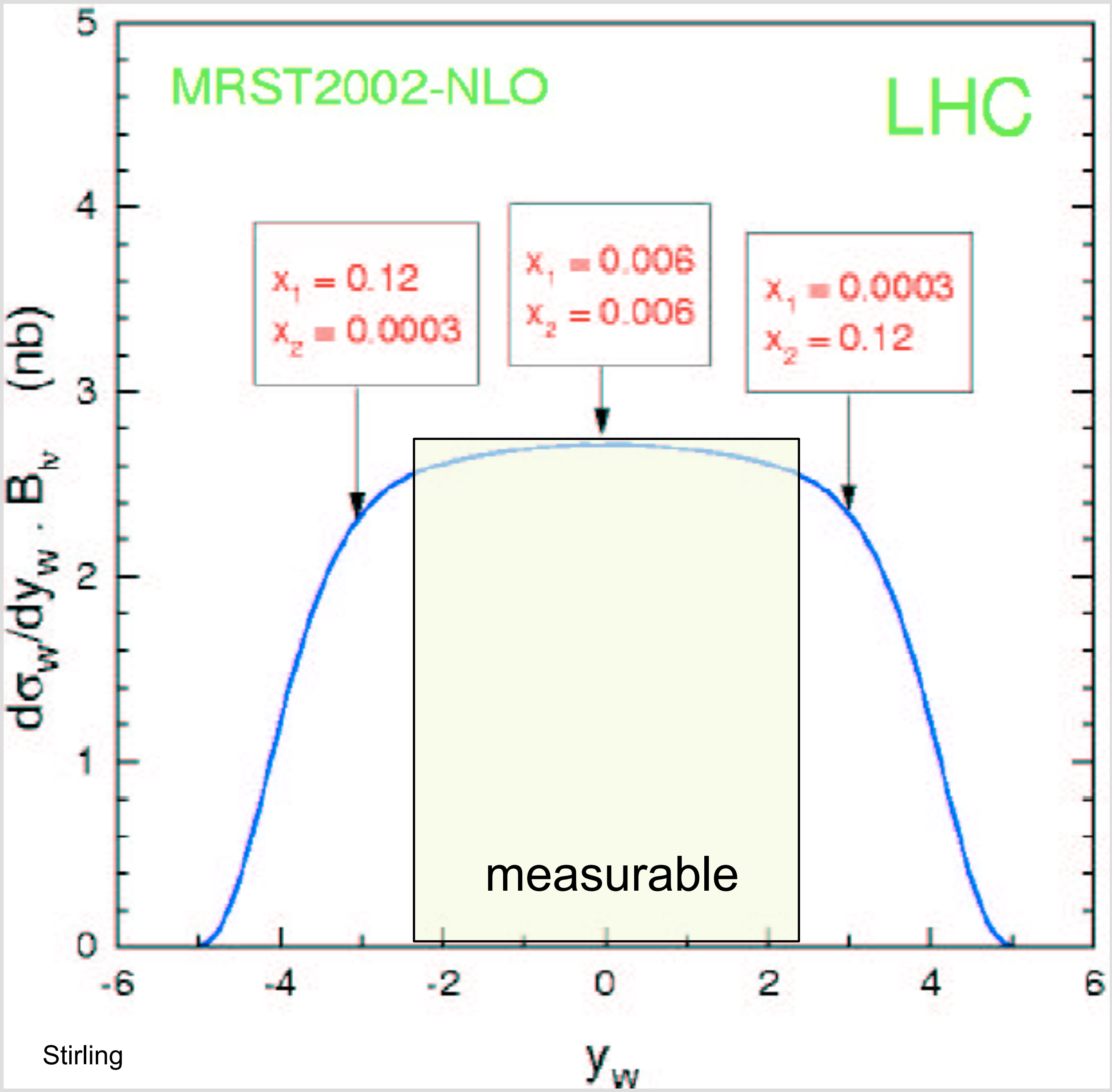
$$\frac{\text{Number of “detectable” objects/events}}{\text{Number of “all produced” objects/events}}$$

example, from MC:

$$\frac{\text{N(muons) with } p_T > 10 \text{ GeV and eta} < 2}{\text{N(all generated muons)}}$$

Issue of acceptance...

- Example: W or Z production



Stirling

- It is a convolution of the acceptances for the leptons
- **Do we really want to correct for acceptance?**
- **Pros:**
  - The cross section measurement can be directly compared to other (corrected) measurements, from other exps
  - The measurement can be compared to theory predictions which cannot be obtained for arbitrary acceptance
- **Cons:**
  - The measurement becomes model dependent
  - we introduce a systematic error, eg. because of uncertain extrapolation to full acceptance

Issue of acceptance...

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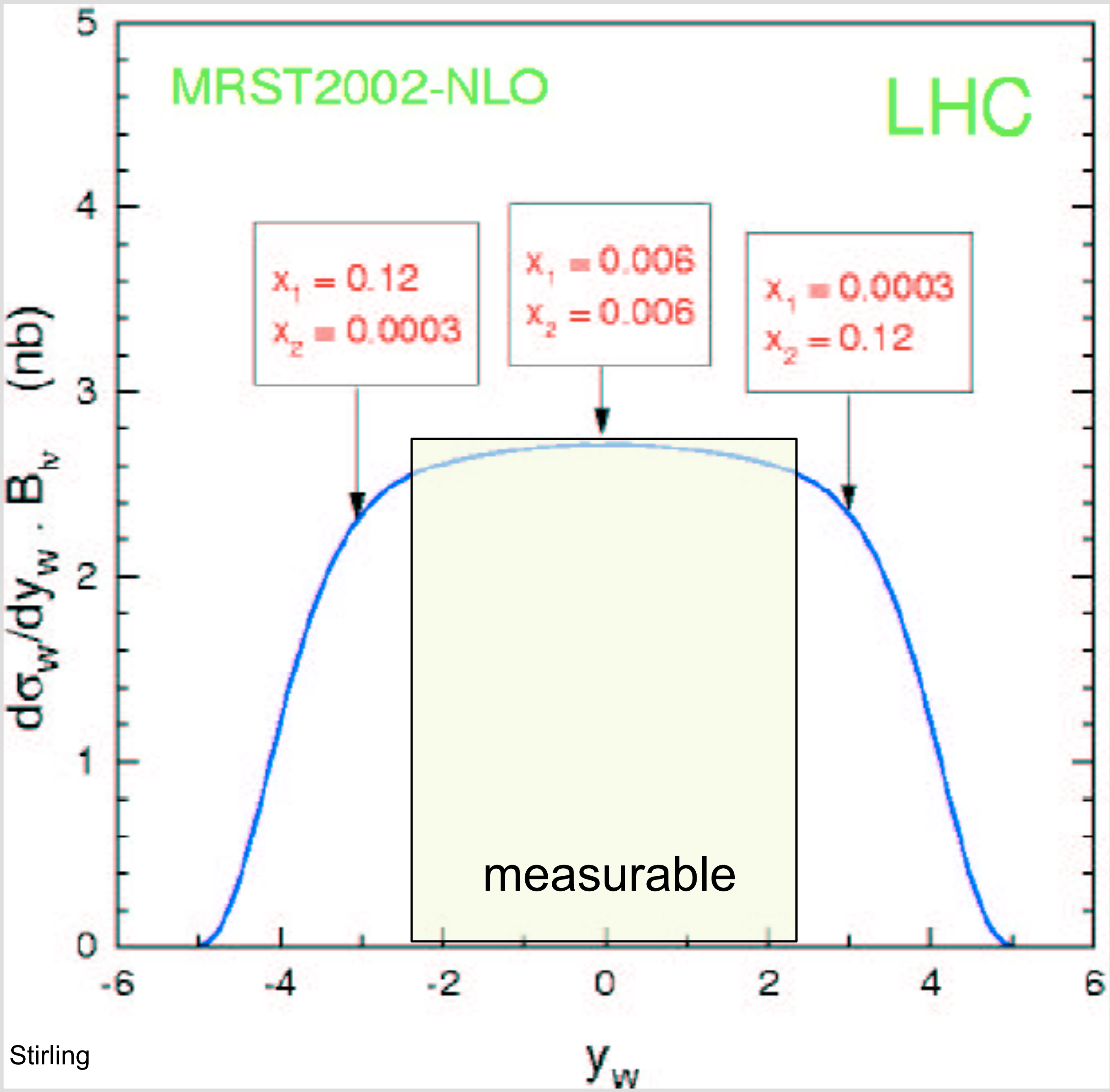
- Example: W or Z production



if we want **precise measurement** of Luminosity or some parameter in hard-interaction cross section, it is essential to have HO calc.

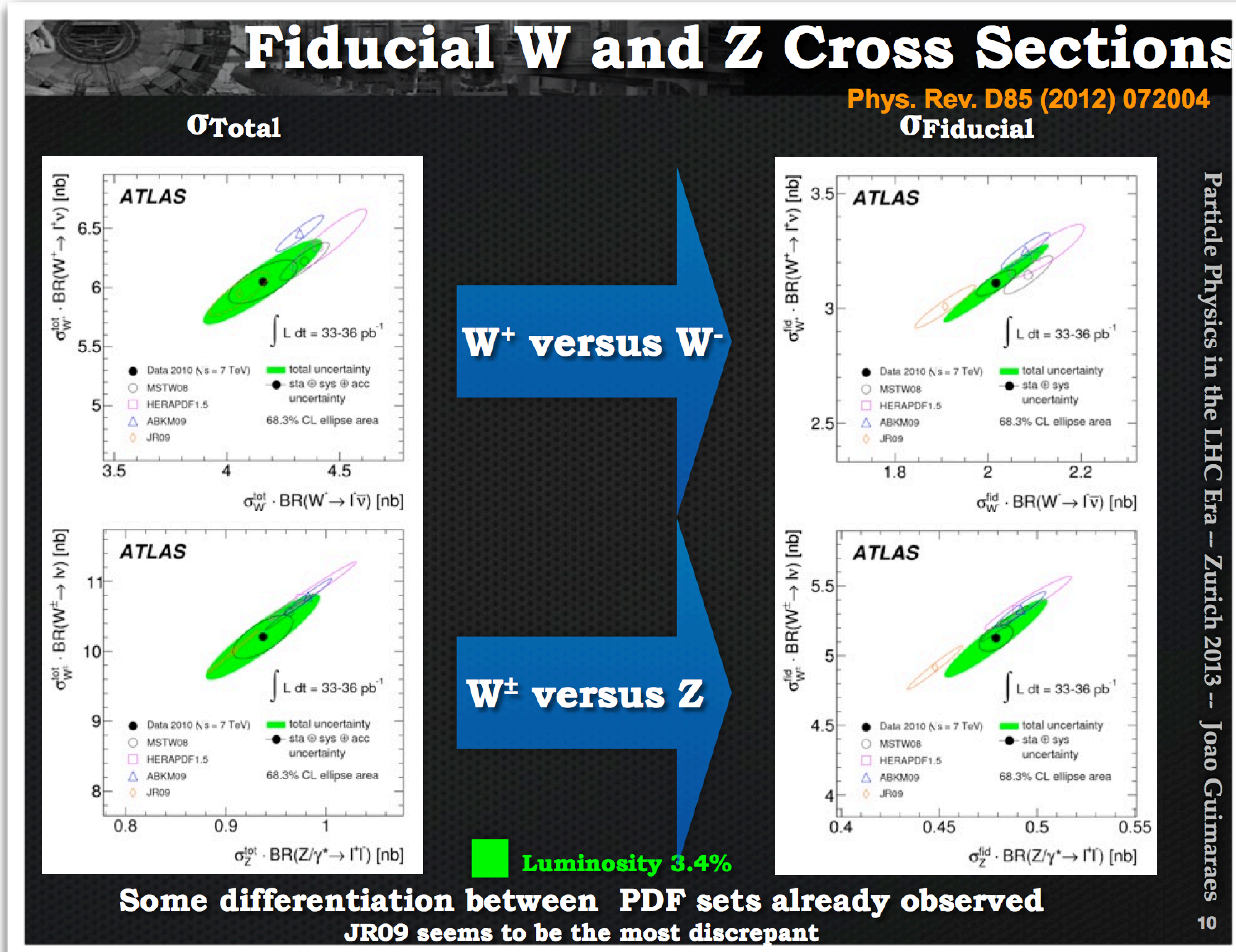
restricted to measurable acceptance

$\Rightarrow$ avoid **extrapolation errors**

eg. from extrapolation to large y_W where uncertainties from pdfs are large!

... fortunately, nowadays more and more fully differential calculations are available.... thus it becomes possible to calculate “EXACTLY” what is measured.... and such kind of so-called “fiducial cross sections” have indeed been published.

Fiducial cross sections...



Trigger efficiencies

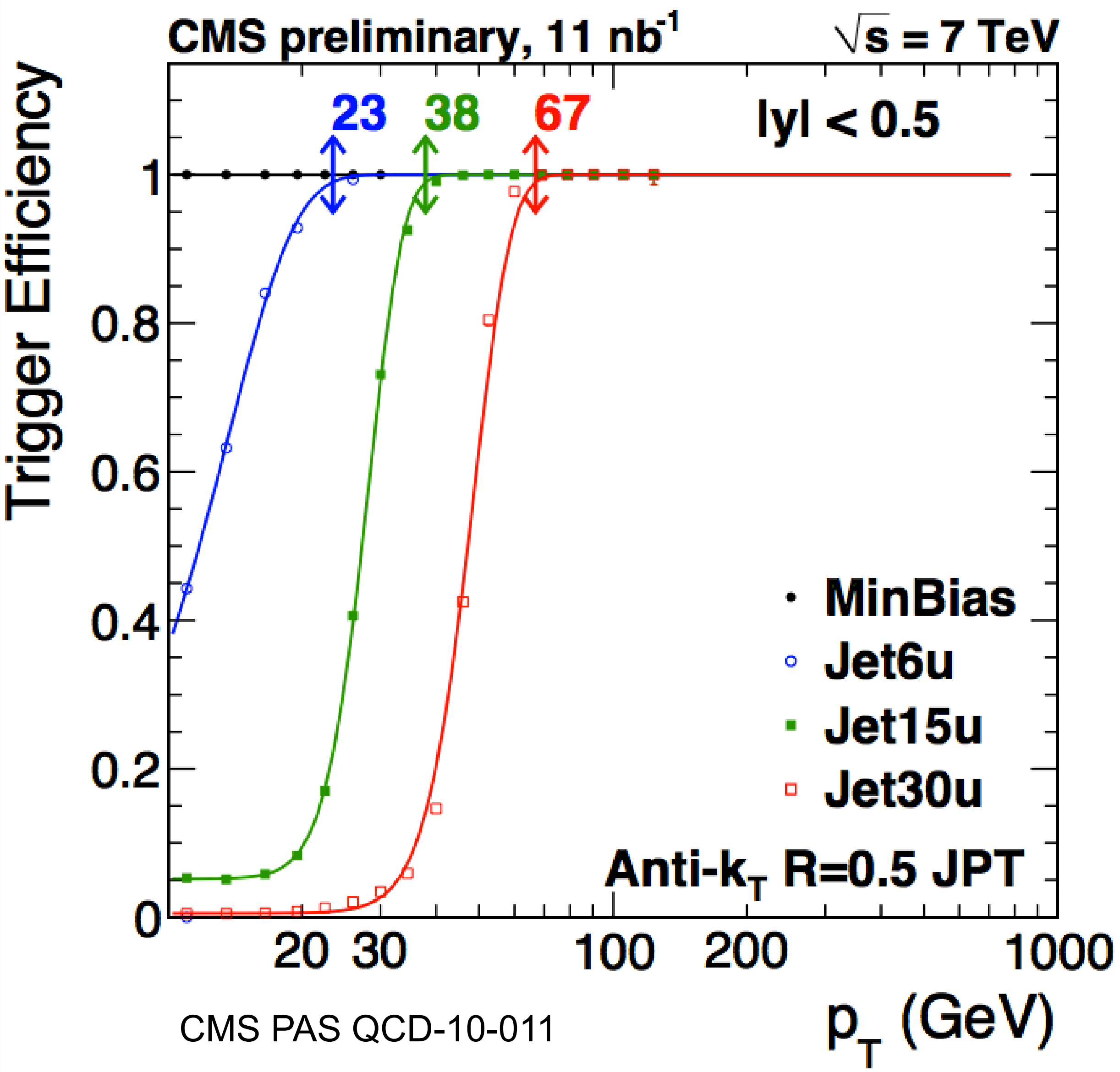
- **Usual recipe**: try to have a "more inclusive" trigger, where you "know" that it is "100% efficient", and calculate rate w.r.t. this one
- Example: trigger rate for a Jet Trigger with E_T>15 GeV:

$$\epsilon_{TRIG} = \frac{N(\text{ Jet15 Trigger AND MinBias Trigger })}{N(\text{ MinBias Trigger })}$$

- **Minimum Bias Trigger**: a minimal set of selection criteria are applied, eg. a few hits in the beam scintillation counters
- compare, eg. to **Zero Bias Trigger**

- Then, the efficiency of a higher Jet ET trigger, eg. 30 GeV, can be found from:

$$\epsilon_{TRIG} = \frac{N(\text{ Jet30 Trigger AND Jet15 Trigger })}{N(\text{ Jet15 Trigger })}$$



CMS PAS QCD-10-011

- Typically, apply selection cuts only above a p_T where your trigger is >99% efficient!

The Tag & Probe Method

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- Useful to measure efficiencies from data
  - trigger eff, reconstruction eff., identification eff.
  - eg. single muon trigger eff.: what is the fraction of reconstructed muons, which would also have been triggered on?
  - eg. electron ID eff: what is the fraction of reconstructed electron candidates, which also pass a tight isolation criterium?

$$\epsilon_{ID} = \frac{\text{N(Probes which pass further criteria)}}{\text{N(all tags)}}$$

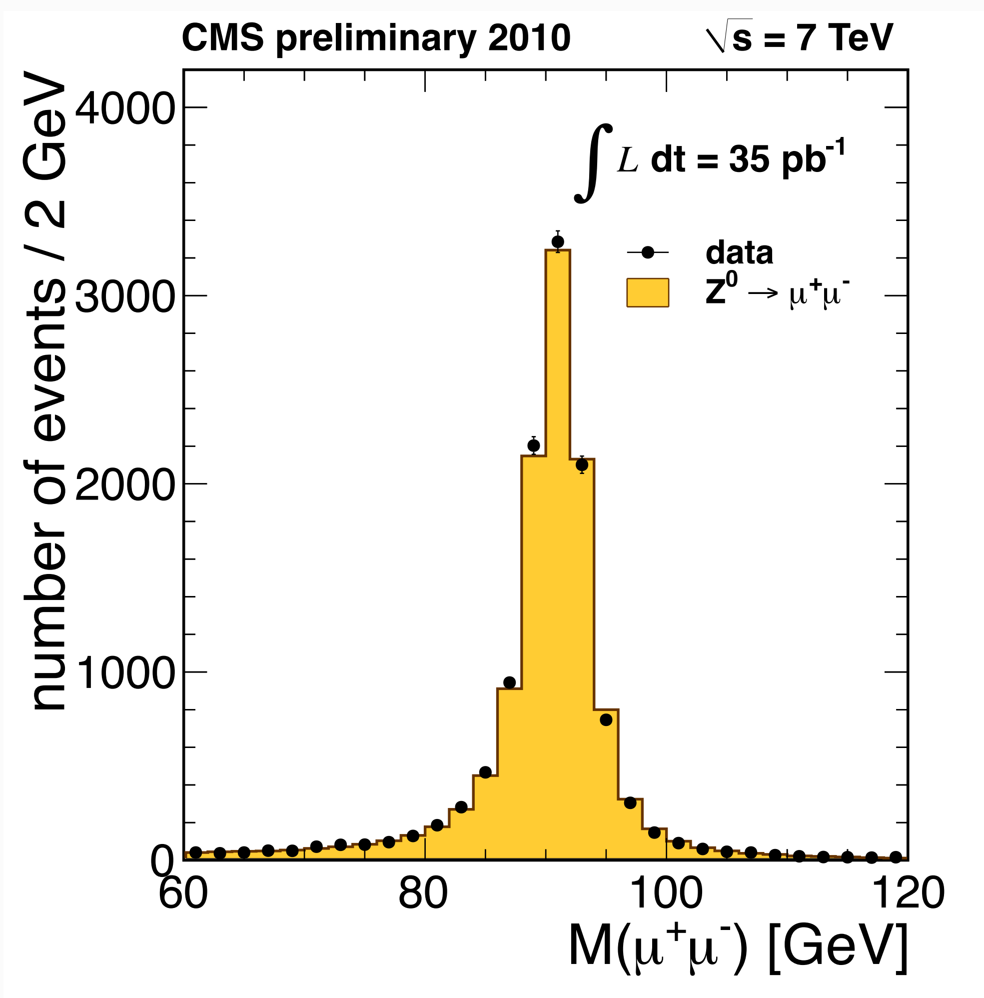
Probe Object: “loosely” selected:
now apply further criteria

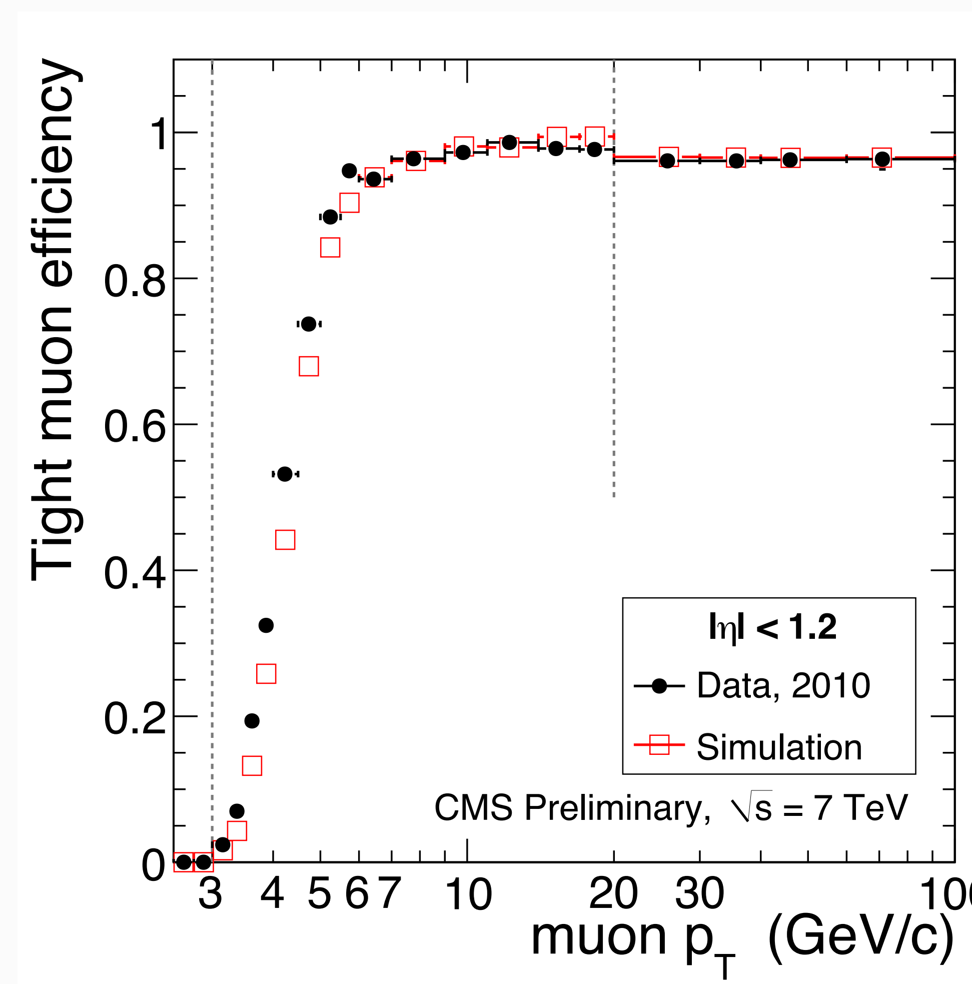
Tag Criterium: eg. di-lepton system close to invariant mass of Z or J/Psi; or a very pure W candidate: one isolated lepton, large MET, no further activity in the event, transverse mass > X

Tag Object: “tight” selection applied:
defined the tag together with the additional criterium above

Tag & Probe....

- **Careful**:
  - make sure no background left, or subtract it
  - make sure no correlations introduced
- Apply same method in data and MC.
  In MC: compare to "True Eff." and if necessary apply (hopefully small) additional correction factors, if some bias is observed





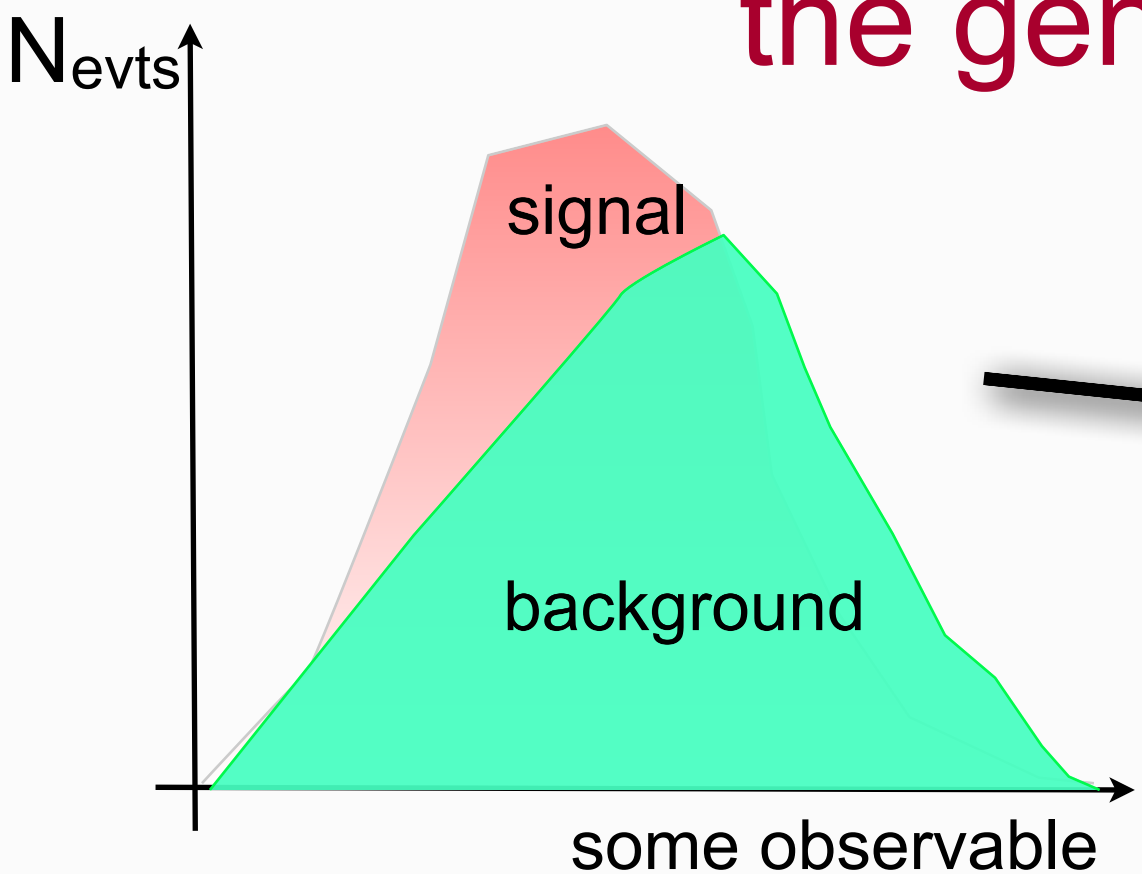
see eg. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO

Backgrounds

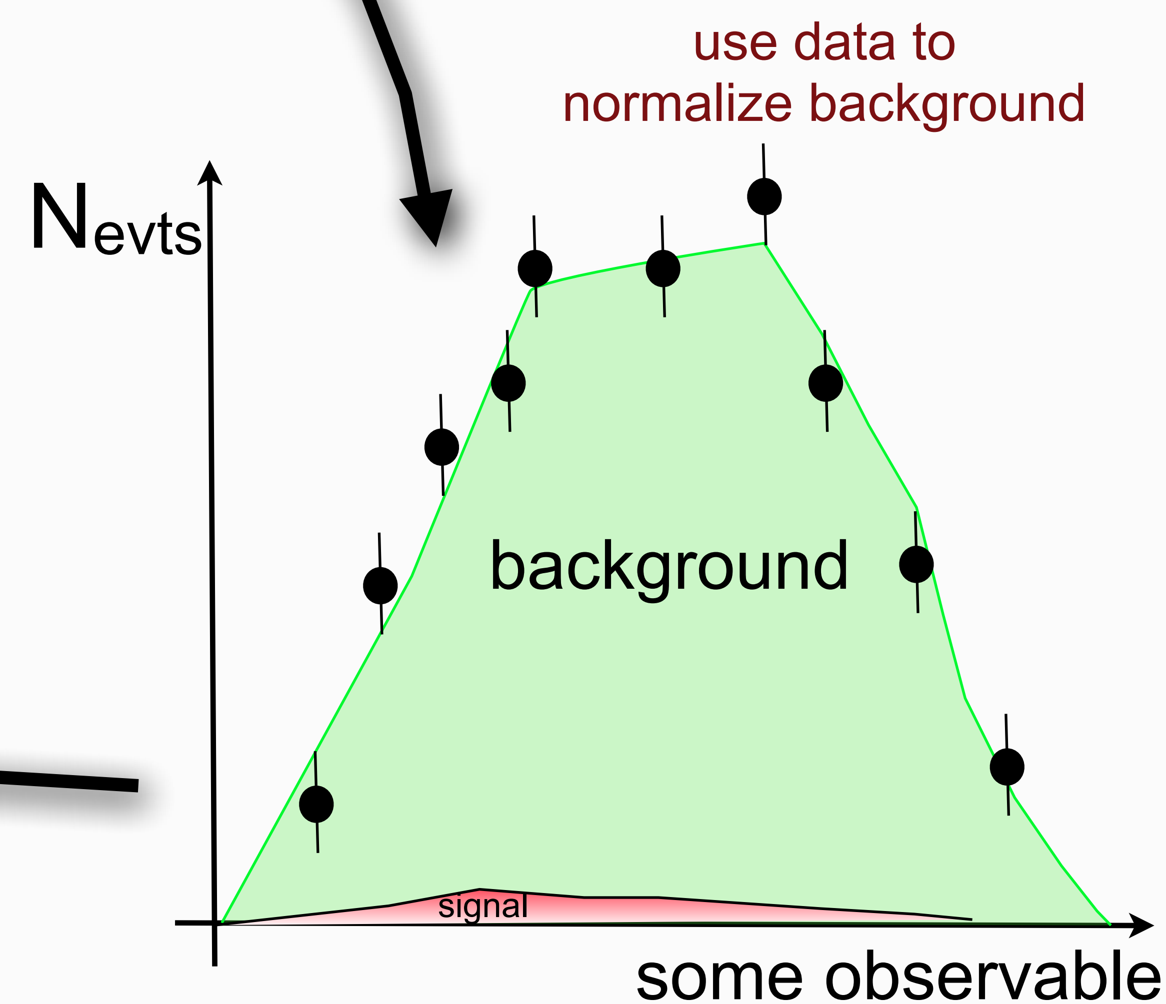
$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \quad L}$$

Data-Driven Background Estimates

the general idea



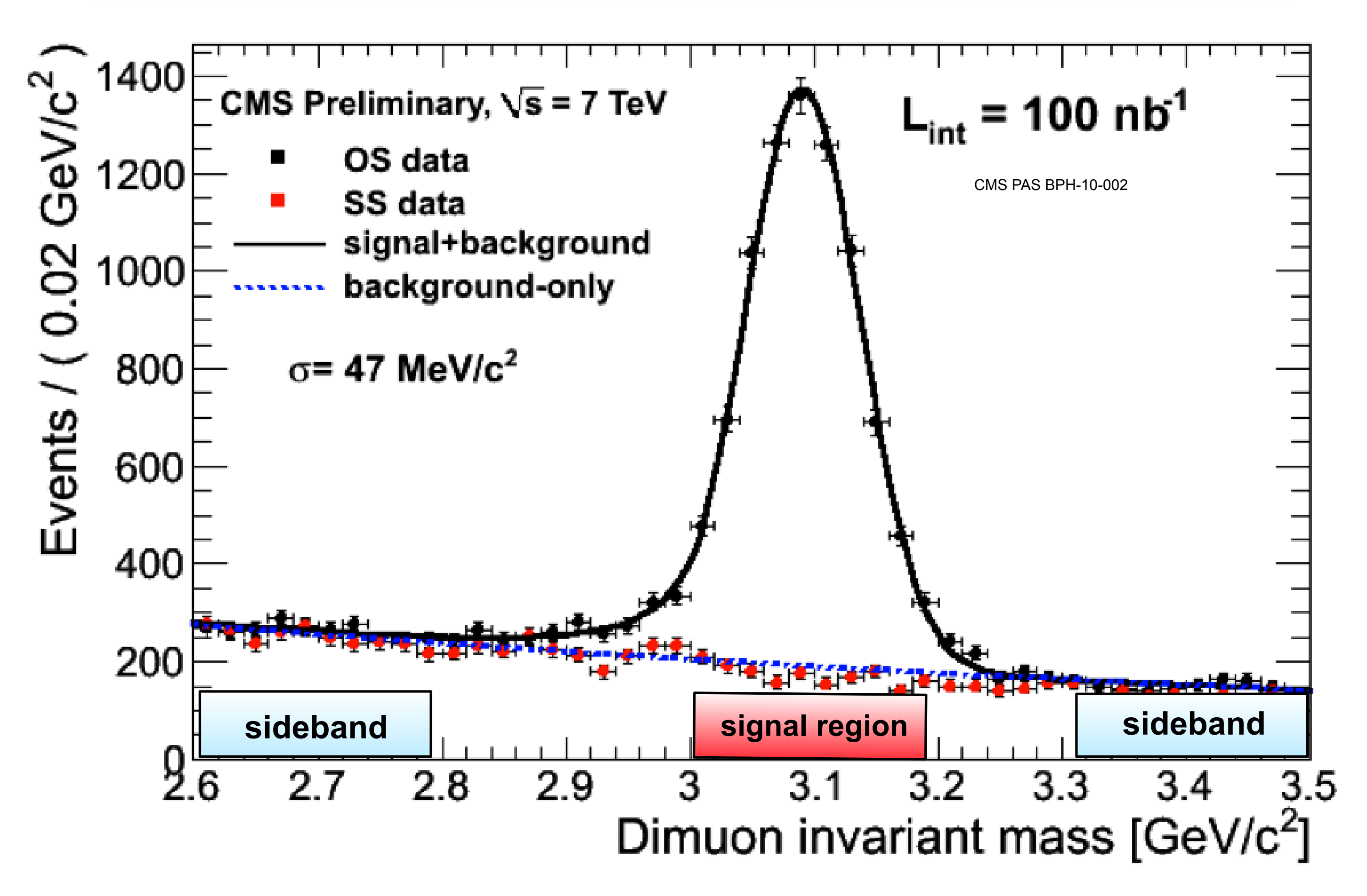
invert cuts :
from signal enhancement to background enhancement



going back:
use theory to compute change in background when inverting cuts, i.e. a ratio **(see later)**;
or use some well-motivated extrapolation, data only **(see next slide)**

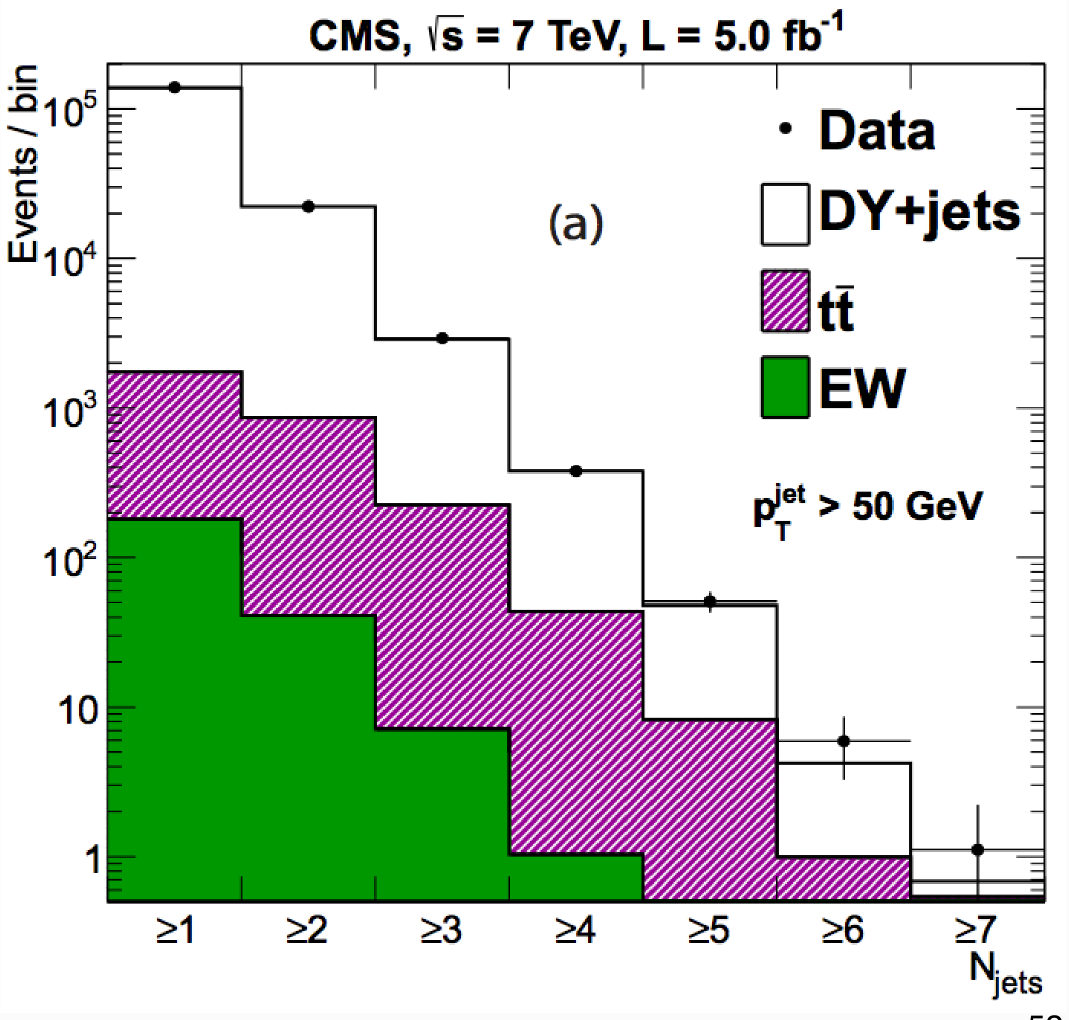
Examples of (fully) data-driven bkg predictions

the trivial case: **sidebands of a mass peak**



ttbar bckg to Z+jets:

take an e-mu dilepton sample with the same kinematic selection as for the same-flavour (ee, mumu) dilepton sample. This is almost pure in ttbar.



Examples of (fully) data-driven bkg predictions

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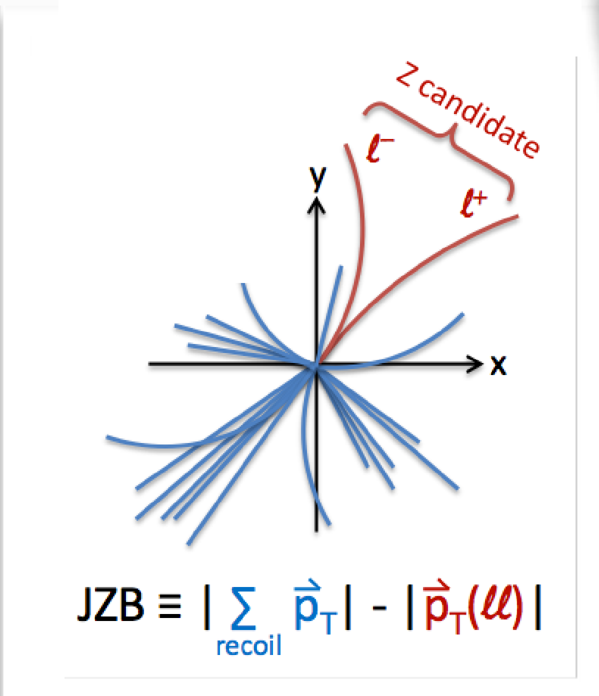
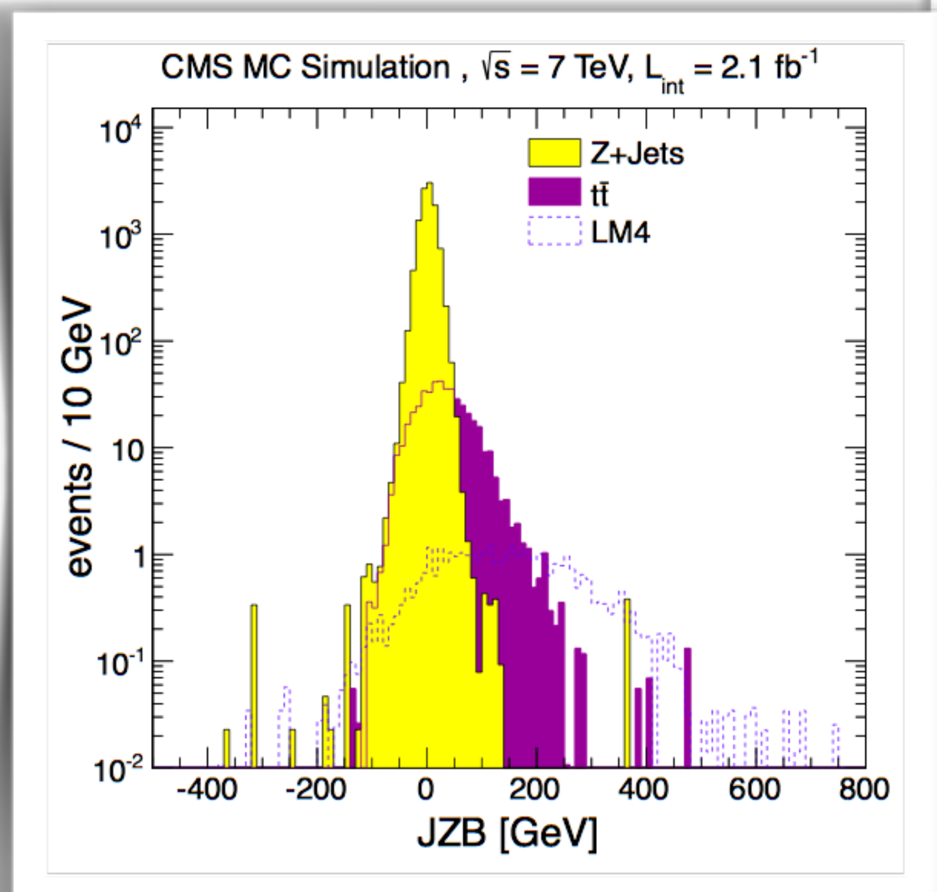
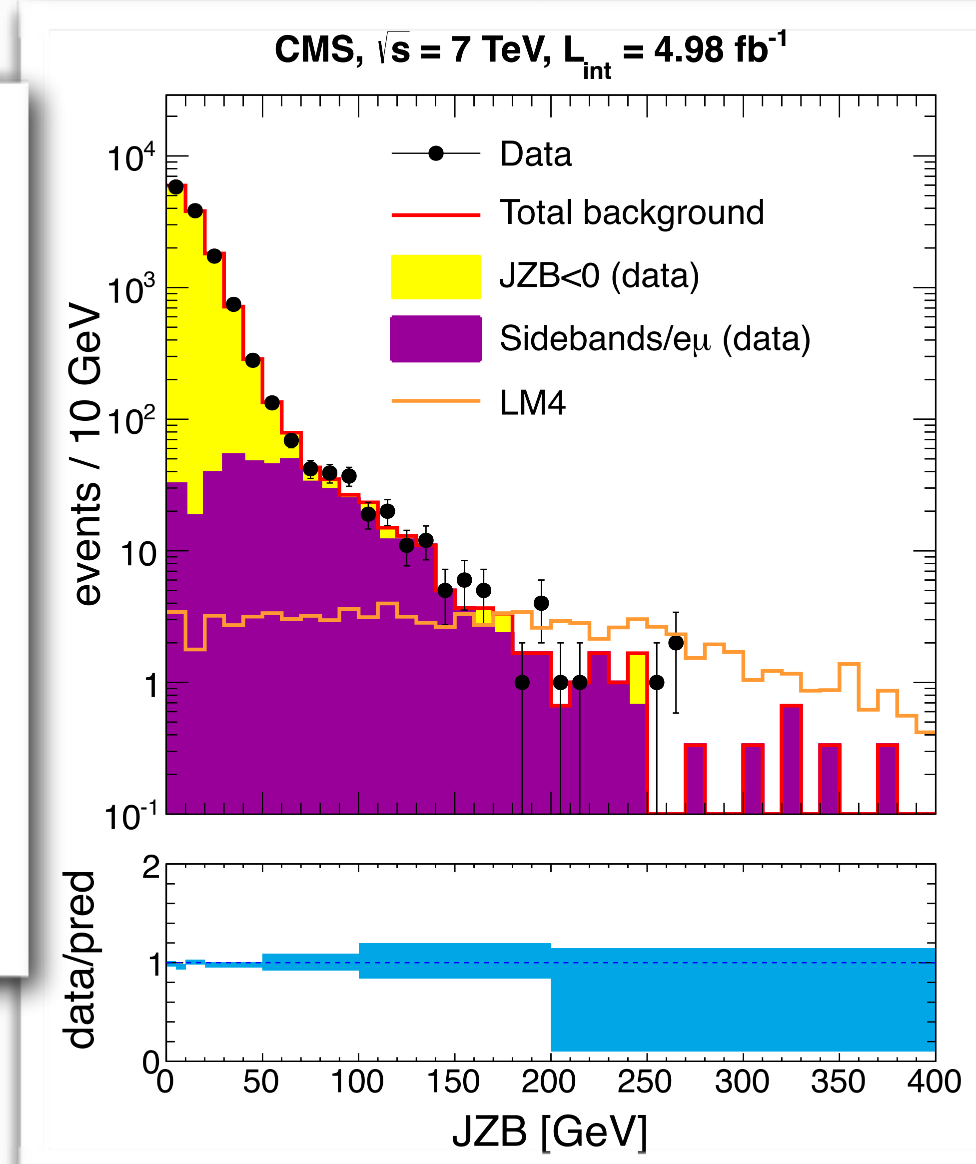
Search for topologies with jets, MET, Z :







- MET in Z+jets events: fake, from jet mis-measurements
- Z+jets bkg on positive JZB: from negative JZB part
- top backg : use opposite-flavour events

arXiv:1204.3774

Often encountered: W selection

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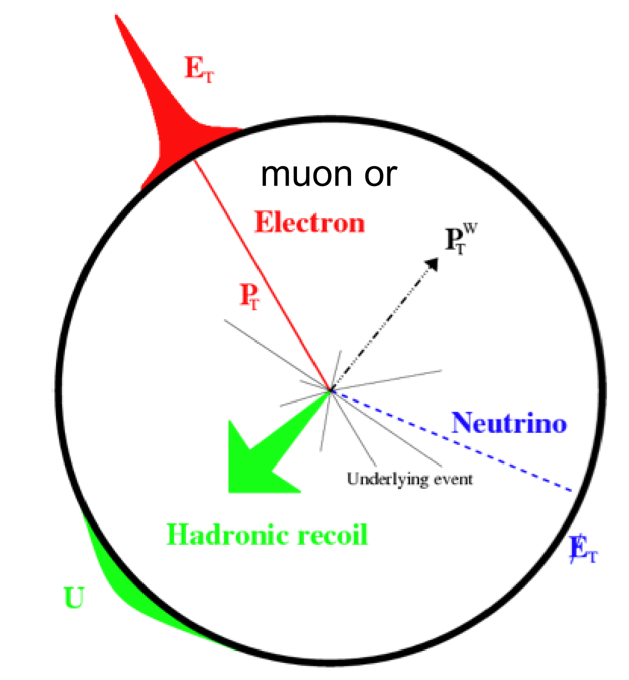
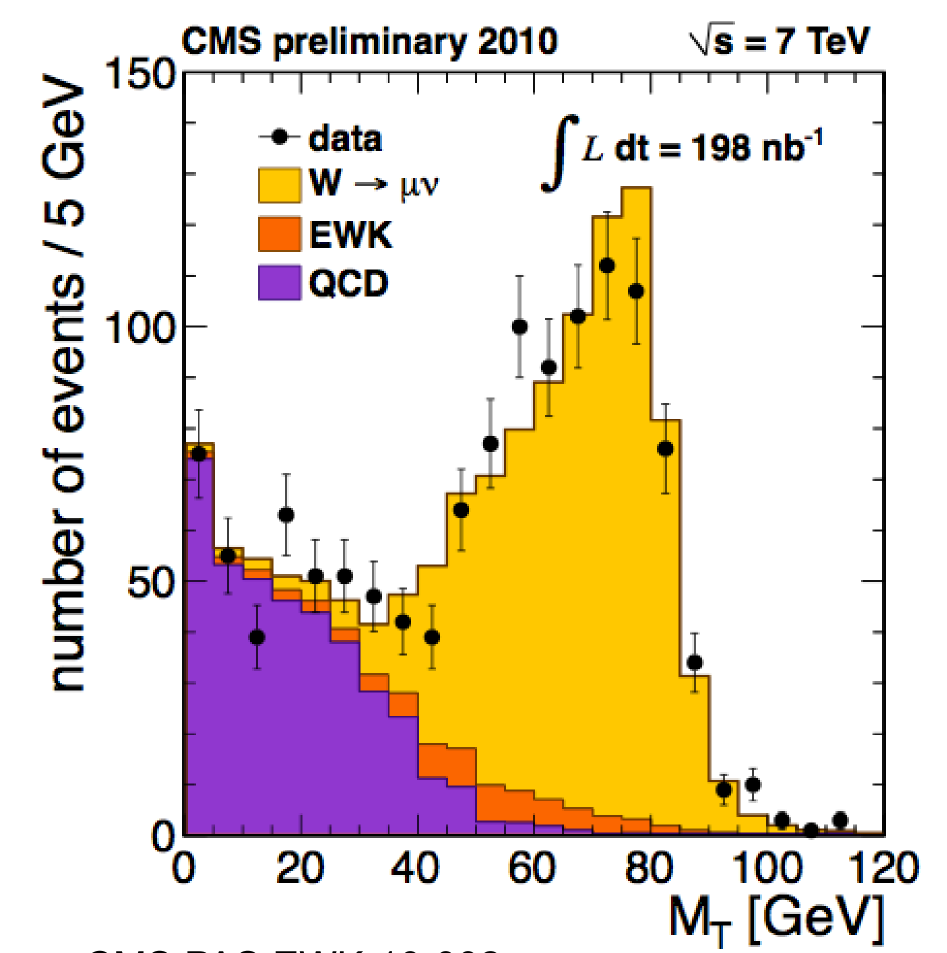


W: decay to charged leptons
- high-p_T
- isolated
- $E_{T,miss}$ (from neutrino)

transverse mass: $M_T = \sqrt{2 p_T(\mu) \not{E}_T (1 - \cos(\Delta\phi_{\mu,\not{E}_T}))}$



CMS PAS EWK-10-002

after cut on important selection variable, the relative isolation:

$$I^{rel}_{comb} = \left\{ \sum (p_T(tracks) + E_T(em) + E_T(had)) \right\} / p_T(\mu)$$

in cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$
around the muon

W selection: cont.ed

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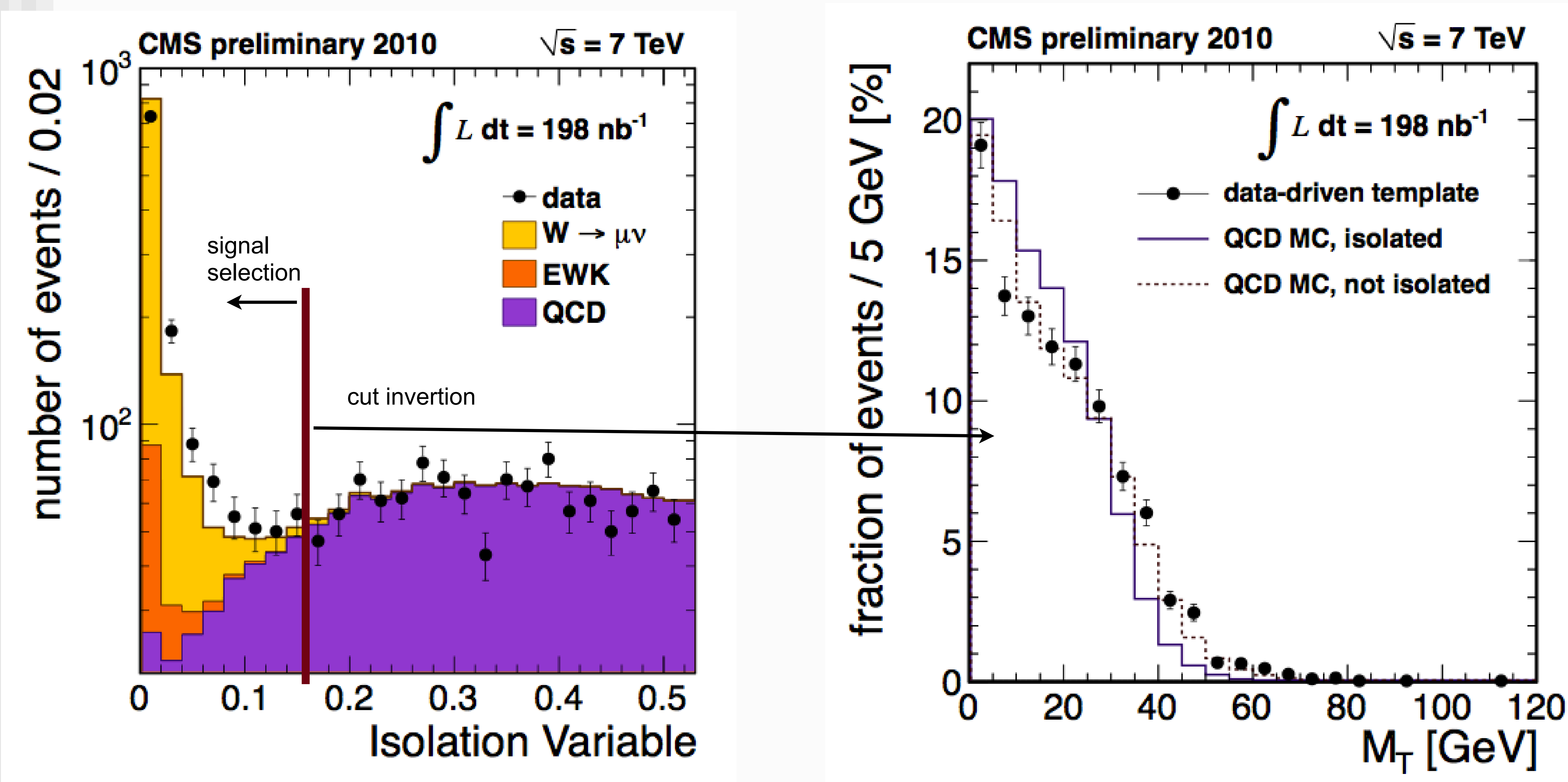
CMS PAS EWK-10-002



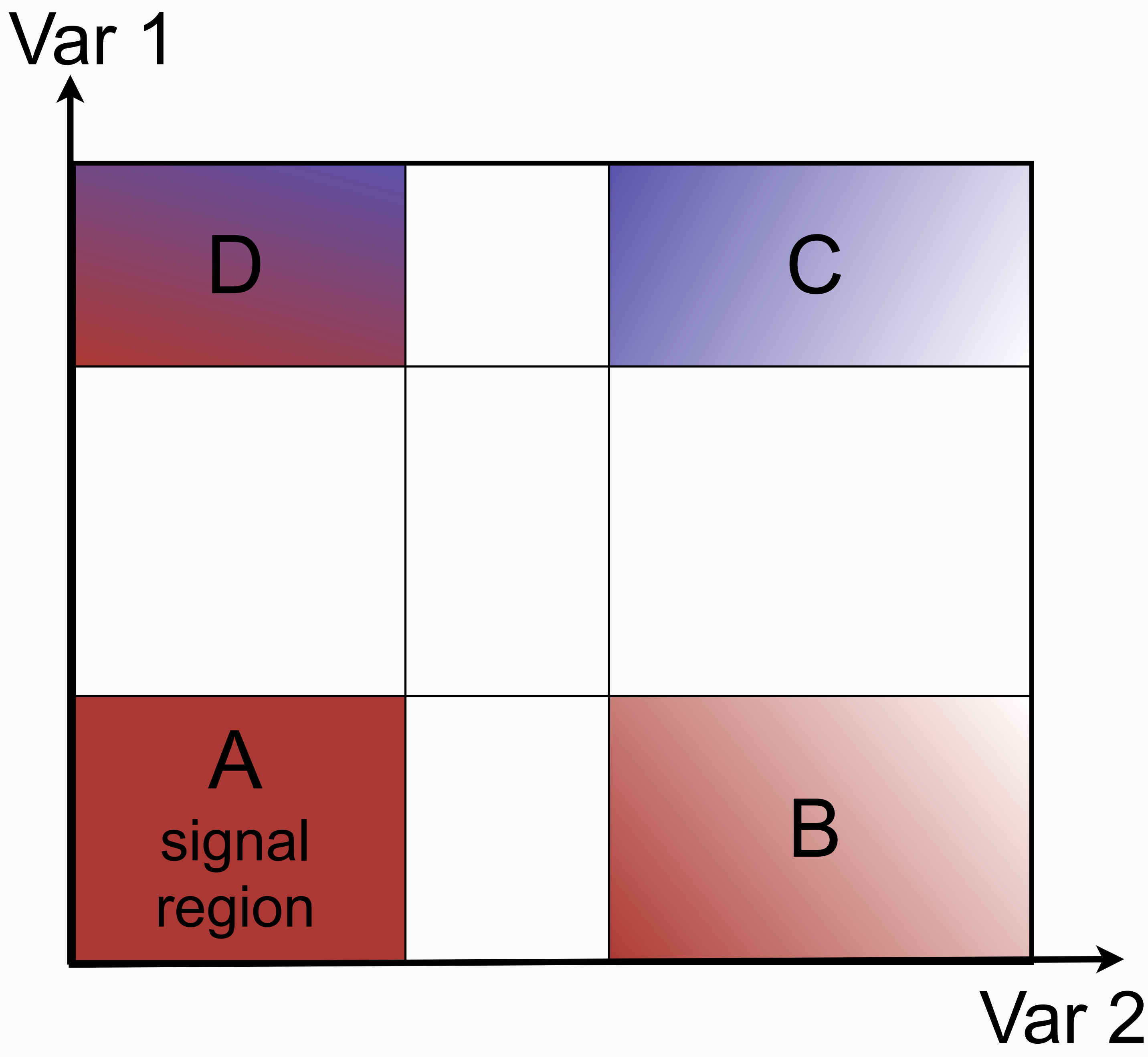
$p_T > 20$ GeV/c in $|\eta| < 2.1$

QCD bkg: mostly b-decays

take this shape for fit to M_T distribution

The “ABCD” method

- find two variables, which characterize the events of interest
- A=signal region, B,C,D: background regions
- hypothesis of **un-correlated** variables:
  background shape in AD sector is the same as in BC sector



If this hypothesis is true, and **no** signal contamination in B,C,D:

estimate for background in signal region is

$$\frac{N(A)}{N(D)} = \frac{N(B)}{N(C)} \Rightarrow N(A)$$

from the counted number of events N(B,C,D) in the background regions.

Often encountered: Fake rates

- What is probability that eg. a jet is mis-identified as an "isolated" lepton?
  - Important to know for leptonic analyses, especially in case of search for rare "multi-lepton" signatures, or e.g., same-sign dilepton SUSY search
  - even if tight isolation requirements are applied, the probability of faking is not zero, and a small number, multiplied with the huge cross section of multi-jet production, can still lead to a sizeable background
  - difficult (impossible?) to trust the simulation on this faking probability, rather try to get it from data?
- "Standard Method":
  "Fakeable Object method", or "Tight-To-Loose Ratio"
  - **Idea** : define two selection steps, one with **LOOSE** criteria, and one with **TIGHT** criteria (eg. on isolation)
  - determine the "**fake ratio**", or "probability for a jet to fake a lepton" from the ratio of tightly to loosely selected objects, in a control sample that should not have any prompt leptons (eg. multi-jet sample)
  - determine this number as function of basic kinematics (p_T, rapidity)
  - apply it to a MC background simulation, or at a preselection level, to determine this fake background on the final selection level

Fake rates: example, tight-loose ratios

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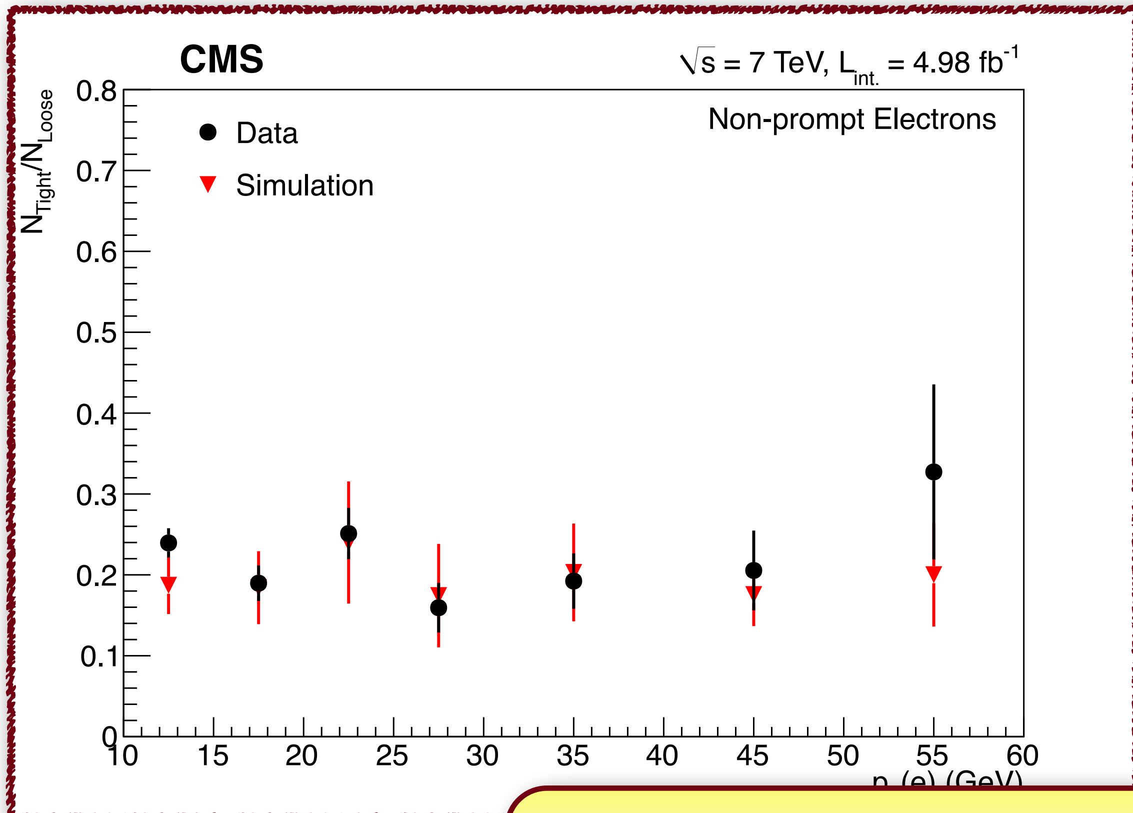
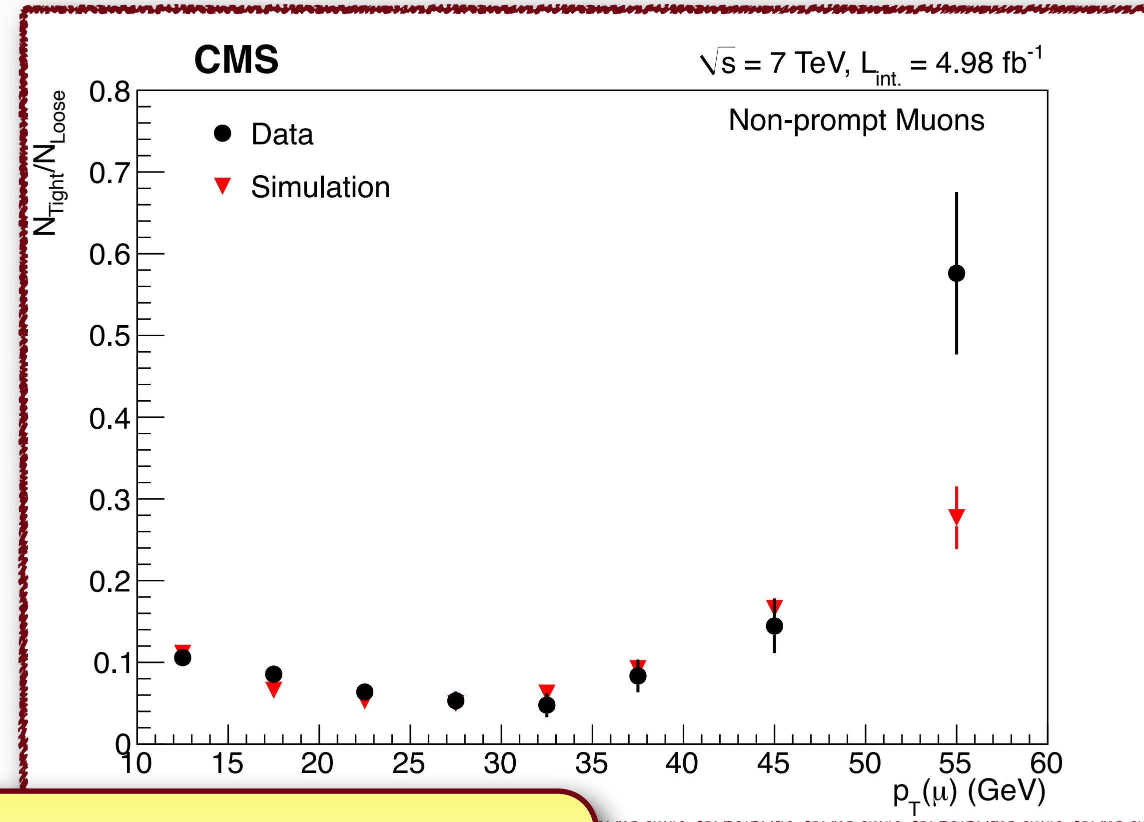
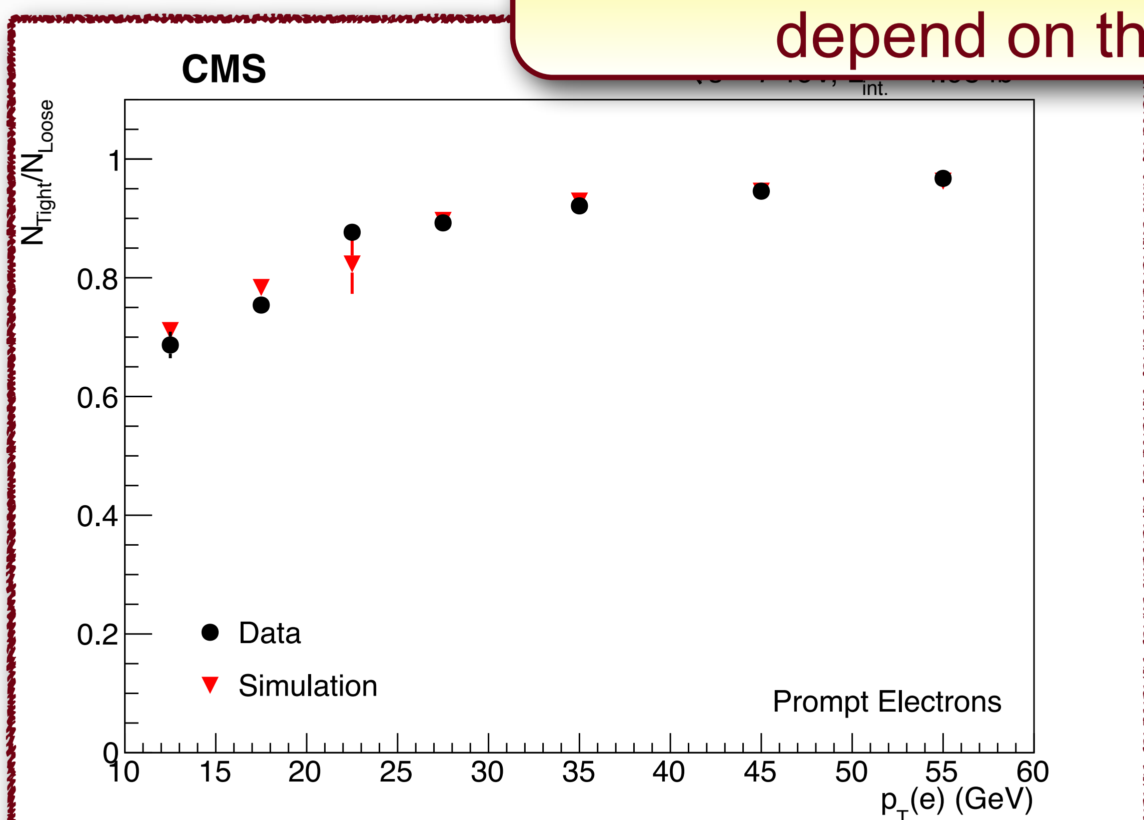
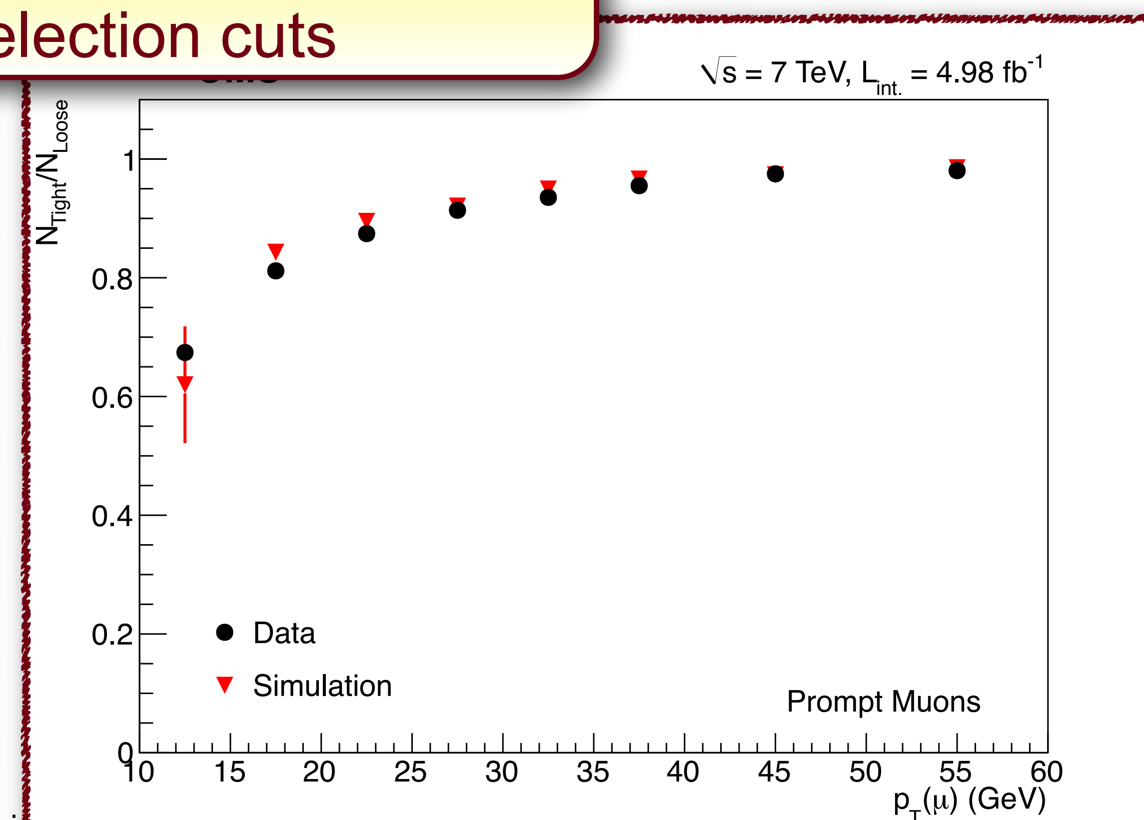
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS110105fb



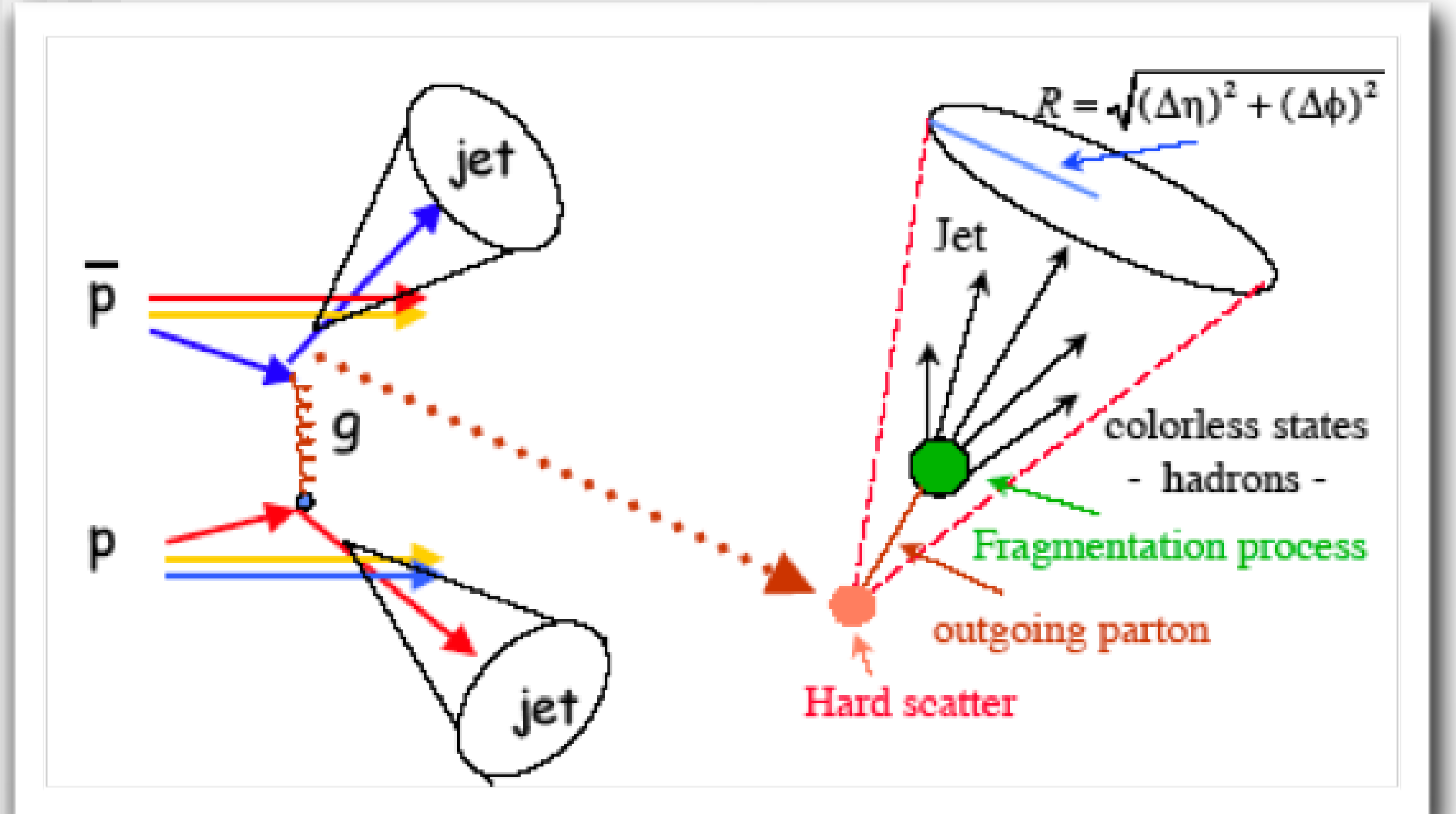


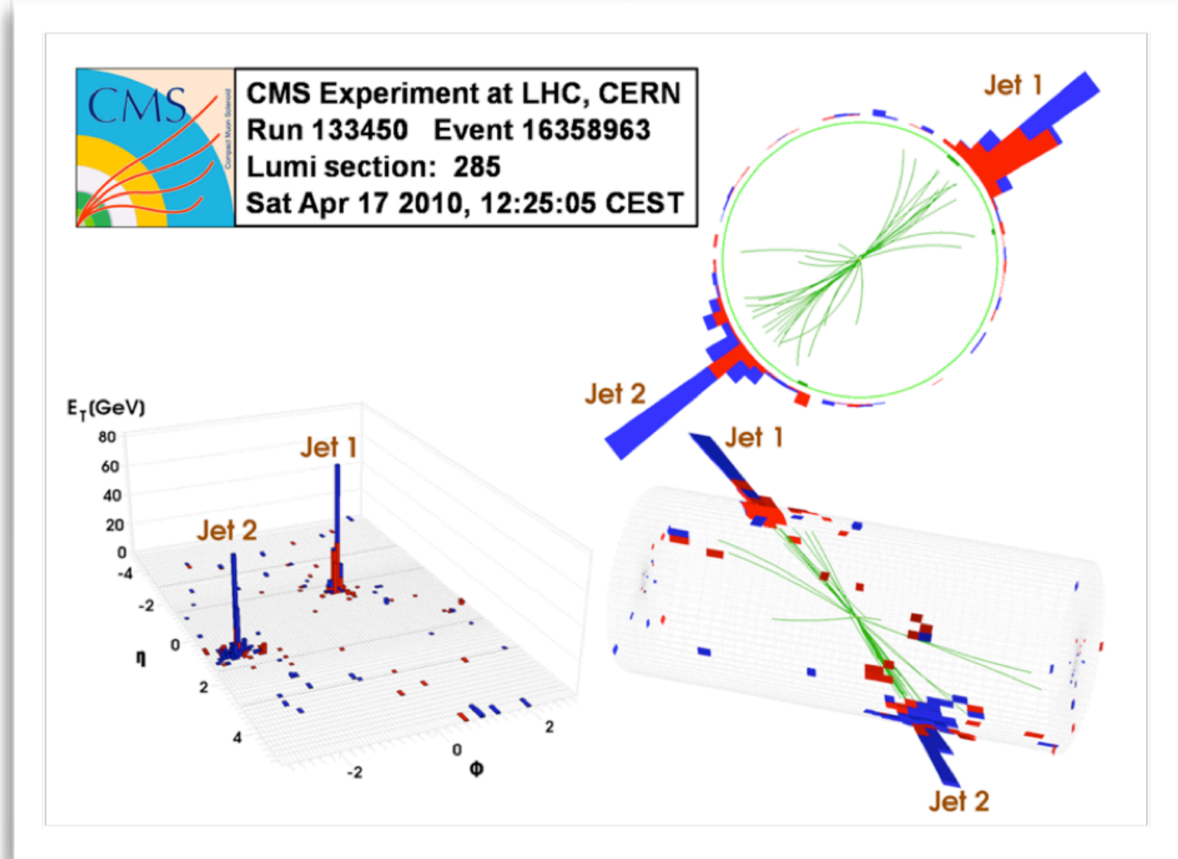
of course, the concrete numbers strongly depend on the selection cuts





Jet Reconstruction and Pile-Up subtraction





Essential tools!

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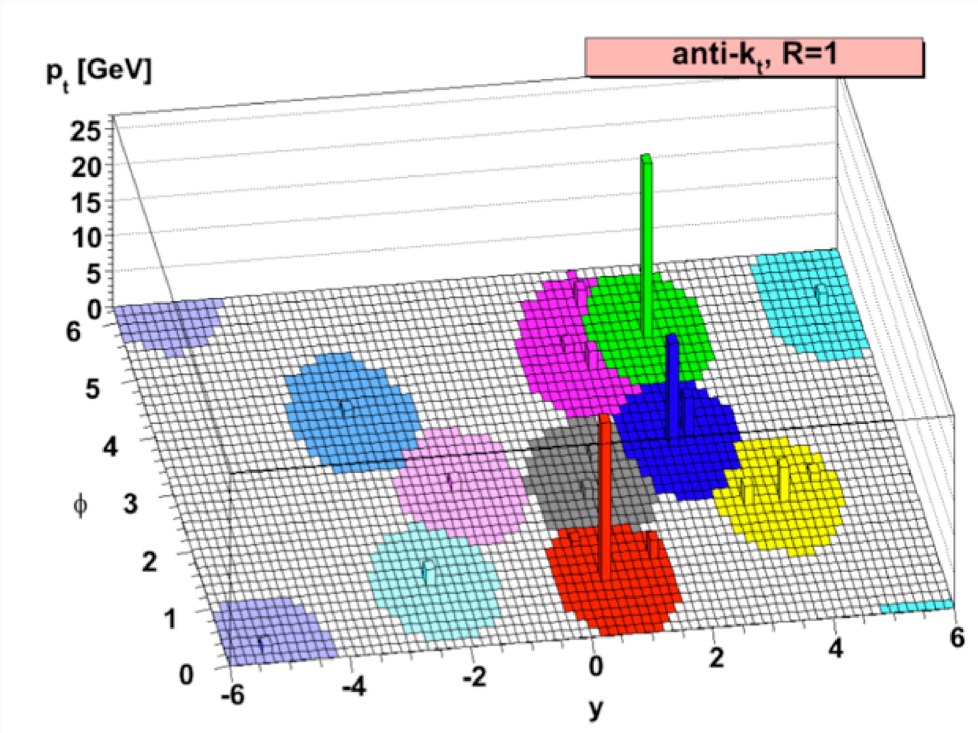
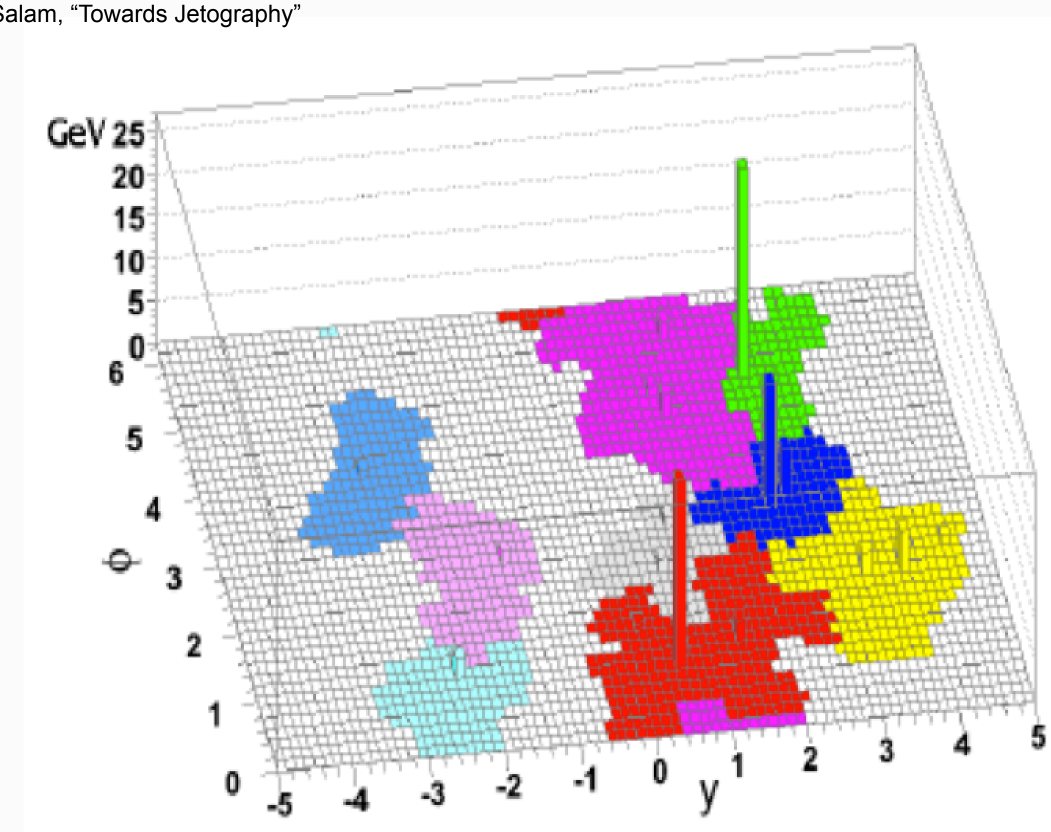
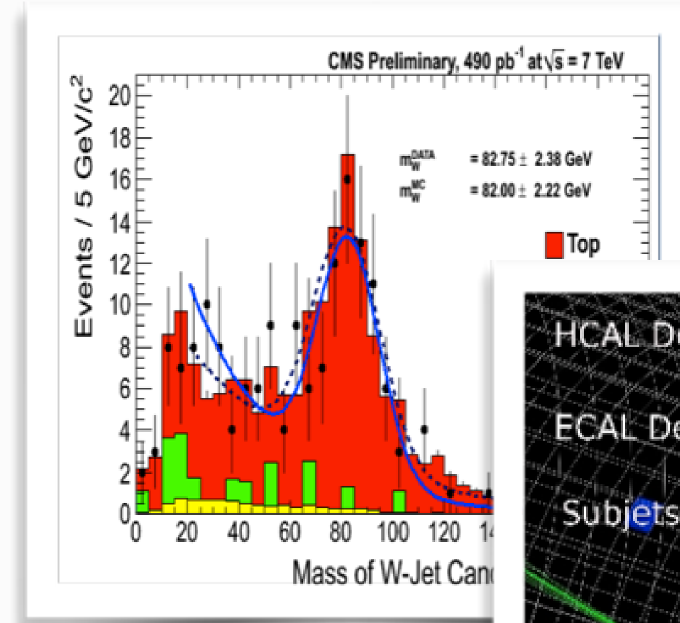
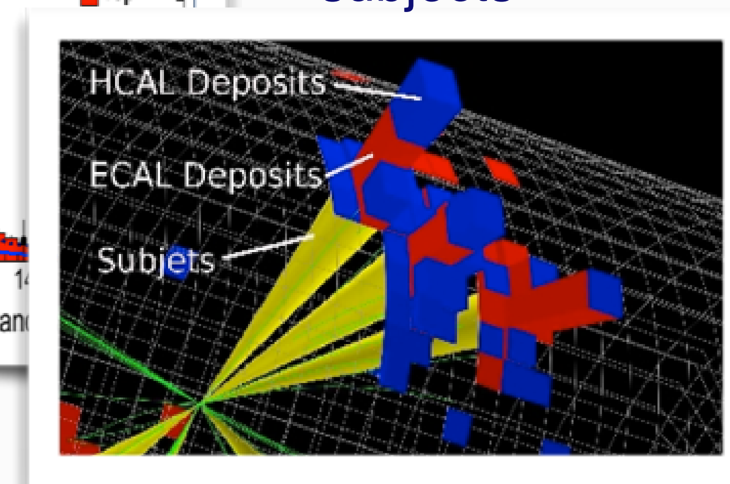


G. Salam, "Towards Jetography"







boosted tops,
top tagging,
subjects

A lot of the experimental success is due to fantastic tools, developed and proposed prior to the LHC startup, such as

- **new jet algorithms (anti-KT)**
- **PU subtraction algorithms**
- **jet substructure scrutiny**

They had a great impact; all proposed, mostly by theorists, only few years ago, but adopted quickly and became standards!

Thus, for the theorists among you: do not only think about super-difficult, non-planar three-loop master integrals, but: **also think about clever observables, clever tools, in order to get out the most from our data!**

Jet algorithms: A bit of history

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- Once upon a time, there were
  - **cone** algorithms (iterative cone, midpoint cone, ...)
  - known not to be infrared and collinear (IRC) safe (i.e., if implemented in a pert. QCD calculation, they would give non-sense and/or infinities at a certain order of pert. theory)
  - there was also the **IRC-safe kT-algorithm** (sequential recombination), but considered to be too slow for application at hadron colliders

- Then came Cacciari, Salam, Soyez
  - first, they developed an IRC-safe cone algorithm (**SisCone**)
  - then they found a clever way to tremendously speed up the kT-algorithm
  - then they generalized the clustering metric, kT became a special case, and another special case appeared and was adopted by the experiments: **the anti-kT algorithm**
  - Then: the fact that the kT (or similarly the anti-kT) algorithm is so fast, allowed them to introduce the jet-area method, which then led to a widely-used pile-up (PU) subtraction method! see later.....

Jet algorithms

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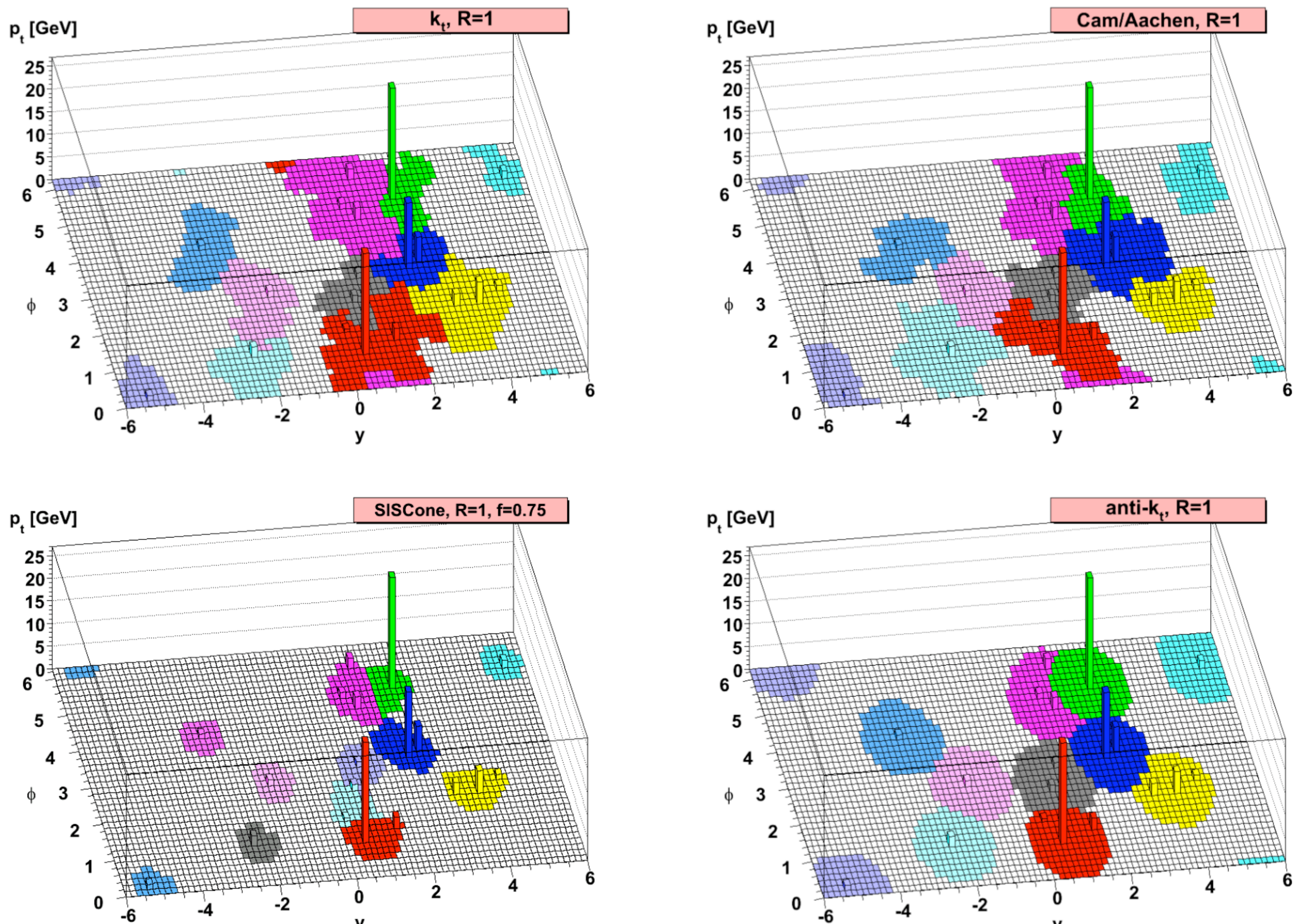
In the past few years, a suite of IRC safe algorithm has become widely used

k_t	SR $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ hierarchical in rel p_t	Catani et al '91 Ellis, Soper '93
Cambridge/ Aachen	SR $d_{ij} = \Delta R_{ij}^2/R^2$ hierarchical in angle	Dokshitzer et al '97 Wengler, Wobish '98
anti-k_t	SR $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2$ gives perfectly conical hard jets	MC, Salam, Soyez '08 (Delsart, Loch)
SISCone	Seedless iterative cone with split-merge gives 'economical' jets	Salam, Soyez '07

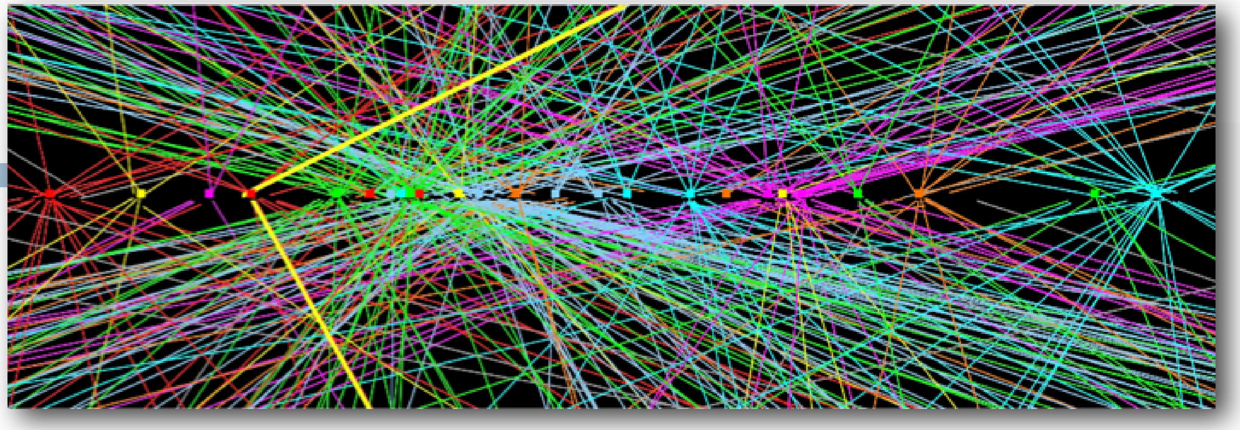
SR=sequential recombination

Jet areas



G. Salam, "Towards Jetography"

Pile-up subtraction

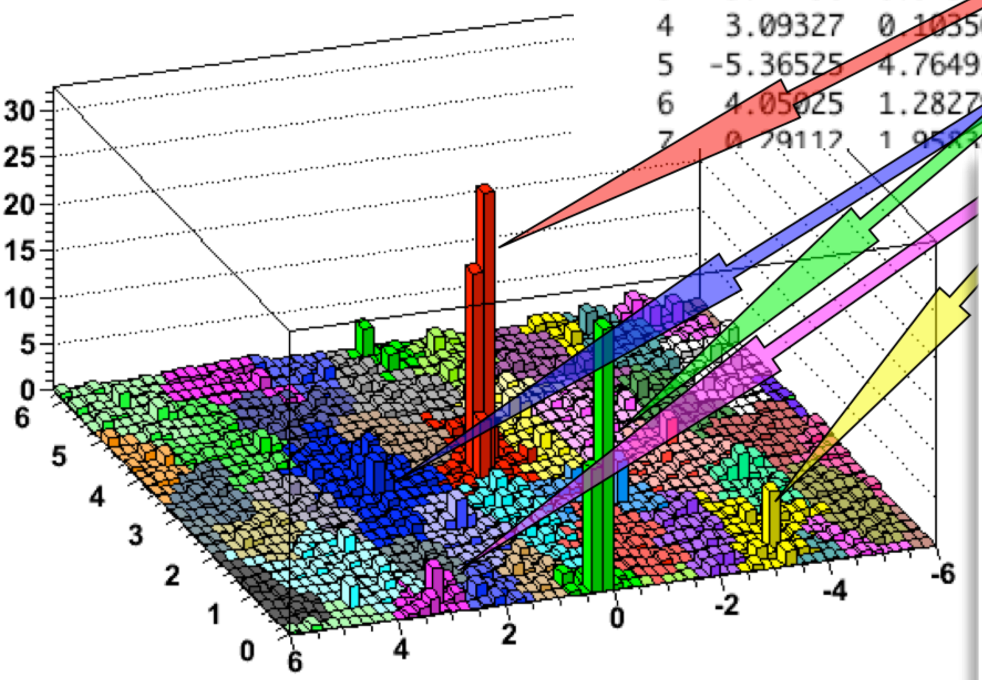


- **A bit of history....**
- Once upon a time, we thought
  - well, if we use a **cone** algorithm, then we get jets with nice cones, where we know the area. Then we measure the average PU energy falling into such an area, subtract it, and we are done
- Then, Cacciari et al. "took us our cone algorithms away". They gave us a fast kT algorithm, but which produces terribly shaped jet areas! What to do now?
- But: since the kT algorithm is so fast, they had the idea:
  - throw into an event a very large number of almost-zero-energy particles ("**ghosts**")
  - run the kT algorithm, find the jets (most of them soft PU jets), and take the **median** of the jet pT over the **"active (or catchment) area"**
  - this is basically the ratio of all ghosts over those ghosts clustered into a particular jet
  - taking the median removes bias from possible appearance of real high-pt jets
- Now there was a way to measure, event by event (!), the average PU energy (or rather pT-) density, which then can be subtracted from the jets, as well as from areas/cones around other objects, such as isolated leptons or photons!!

Pile-up subtraction

A concrete example:
a 50 GeV di-jet event at the
LHC with pile-up
(10 min-bias events added)

```
iev 0 (irepeat 24): number of particles = 1428
strategy used =  NlnN
number of particles = 9051
Total area: 76.0265
Expected area: 76.0265
 ijet    eta       phi        Pt        area  +-    err
   0   0.15050  3.24498    69.970     2.625 +-   0.020
   1   0.18579  0.13150    59.133     1.896 +-   0.020
   2   2.33840  3.23960    31.976     4.749 +-   0.028
   3  -3.41796  0.52394    26.595     3.084 +-   0.021
   4   3.09327  0.10350    20.072     2.688 +-   0.023
   5  -5.36525  4.76491    19.592     2.780 +-   0.012
   6   4.05025  1.28279    15.361     3.592 +-   0.028
   7   0.29112  1.95335    14.566     2.114 +-   0.018
```



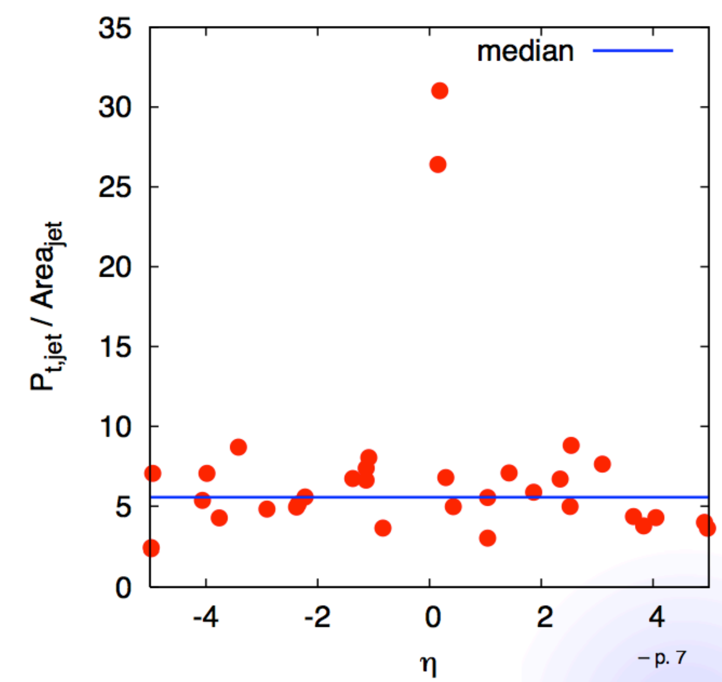
slides from M. Cacciari and G. Soyez

[M.Cacciari, G.P. Salam, GS, 2007-08]

$$p_{t,\mathrm{jet}}^{(\mathrm{sub})} = p_{t,\mathrm{jet}} - \rho_{\mathrm{bkg}} A_{\mathrm{jet}}$$

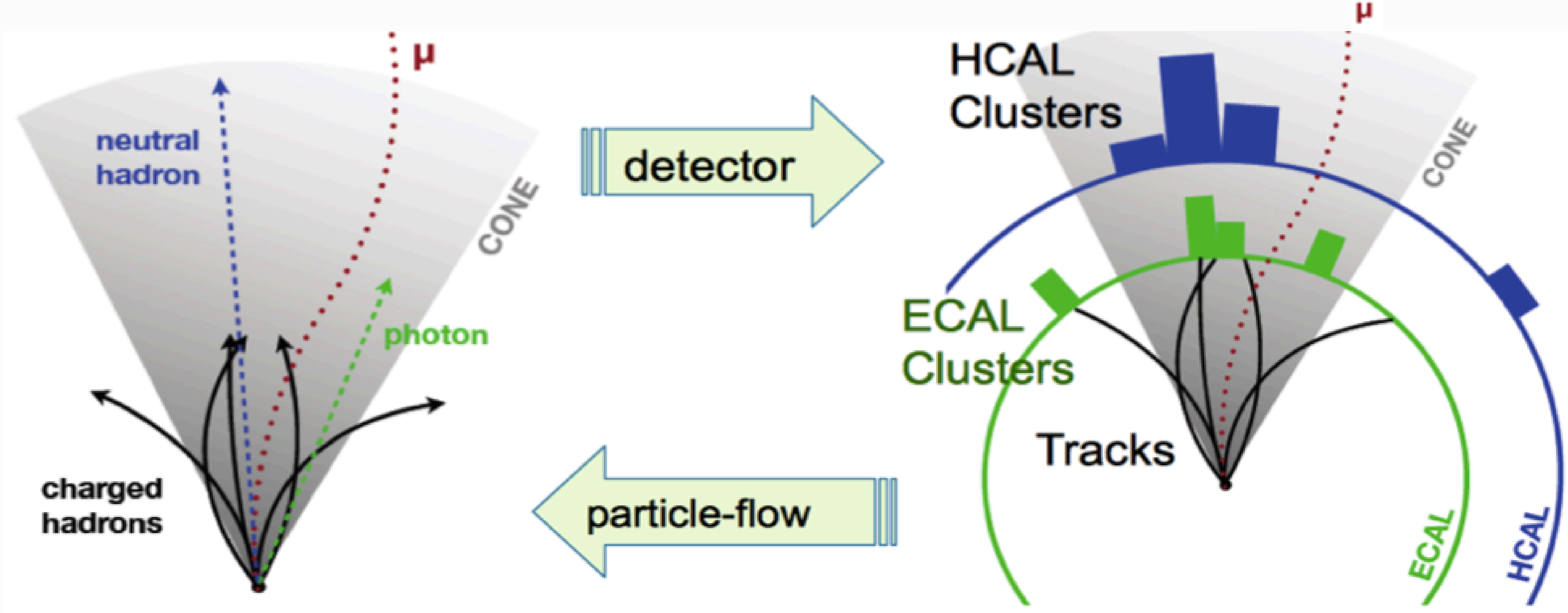
- jet area: available with jet clustering
- ρ_{bkg}, the background p_t density per unit area
  - break the event in patches of similar size *e.g.* cluster with k_t
  - Estimate ρ_{bkg} using

$$\rho_{\mathrm{bkg}} = \underset{j\in\mathrm{patches}}{\mathrm{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$



Particle Flow and Consequences

Use of global event description



- Charged particles well separated in large tracker volume & 3.8T B field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution
- In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)
- Therefore: **Use a global event description** :
  - Optimal combination of information from all subdetectors
  - Returns a list of reconstructed particles (e,mu,photons,charged and neutral hadrons)
  - Used as building blocks for jets, taus, missing transverse energy, isolation and PU particle ID

The Pflow jet composition

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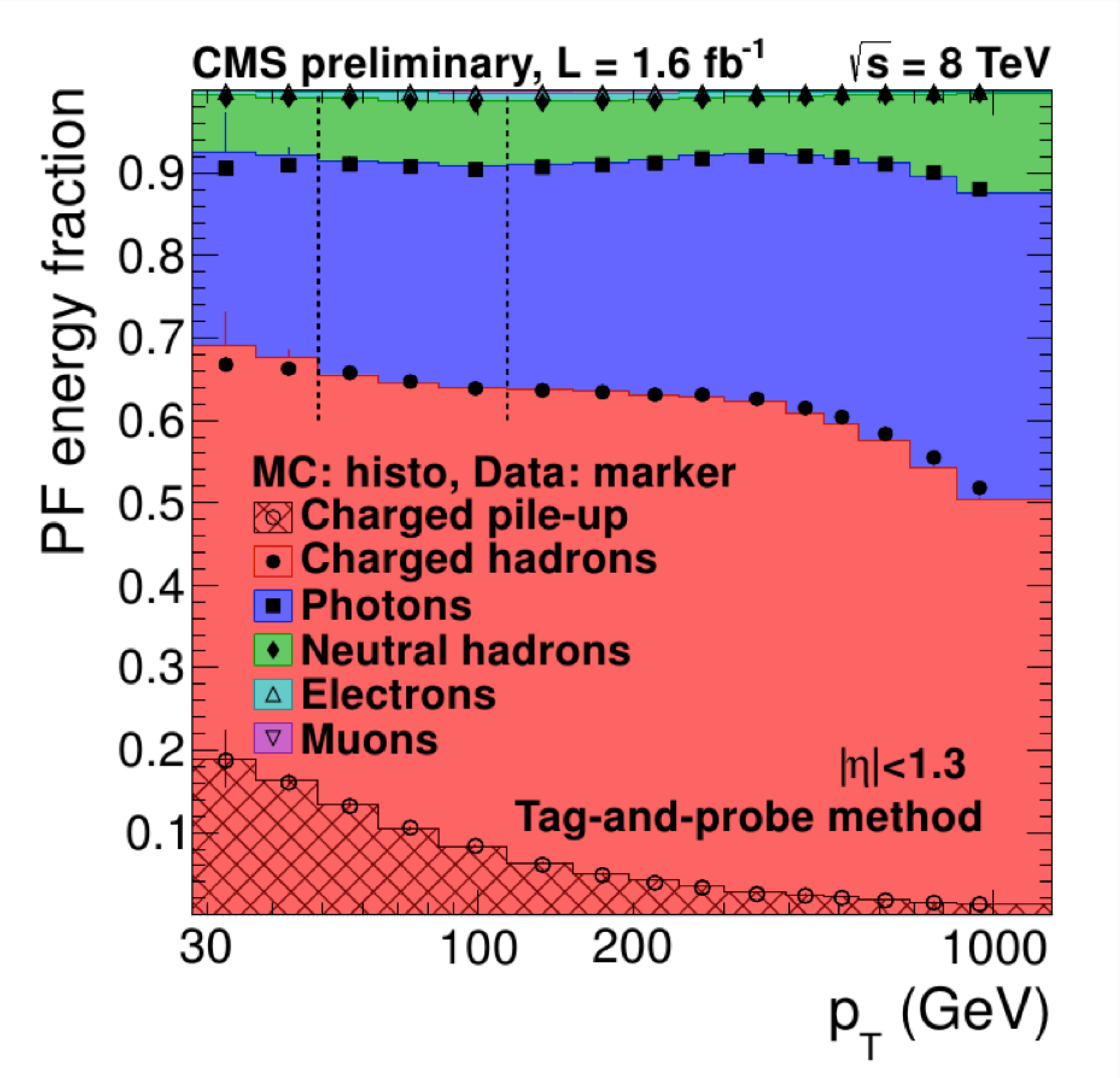
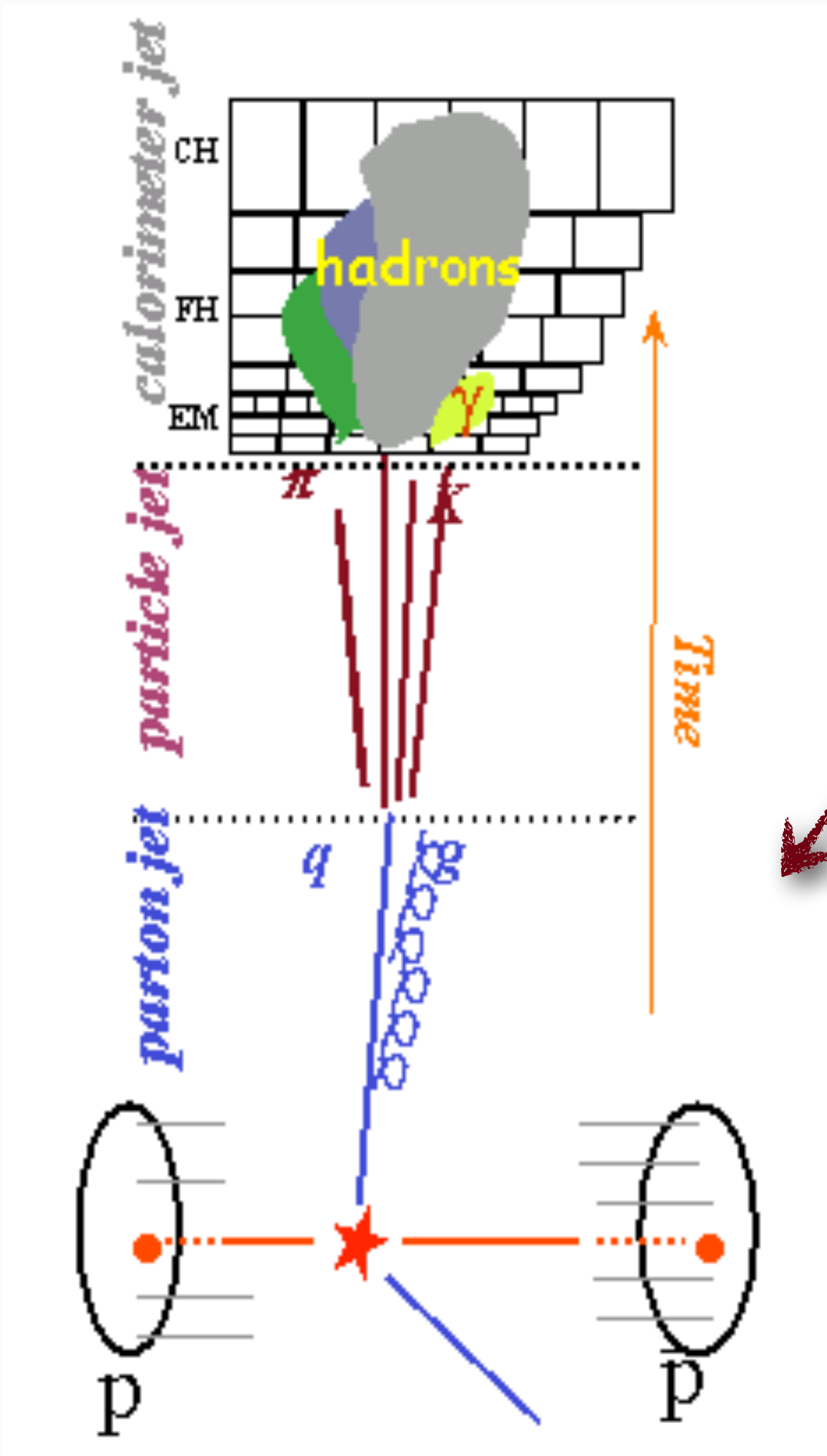
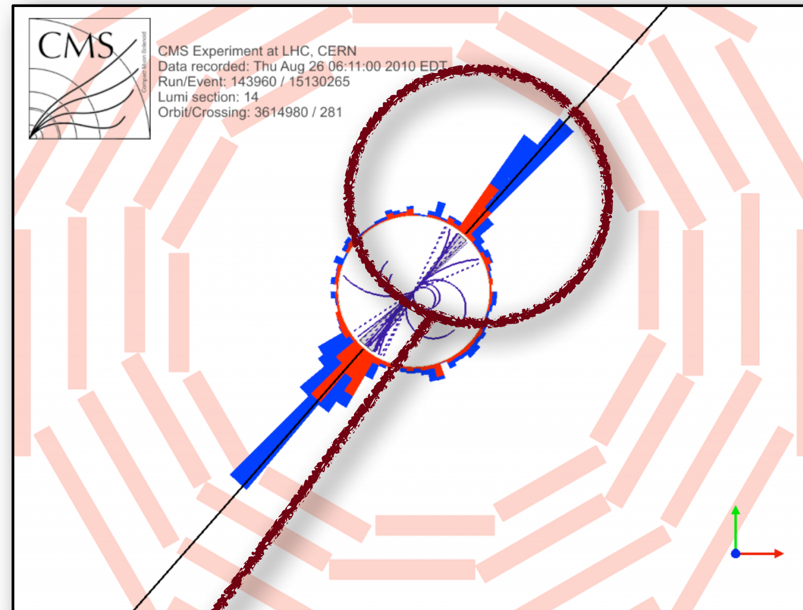
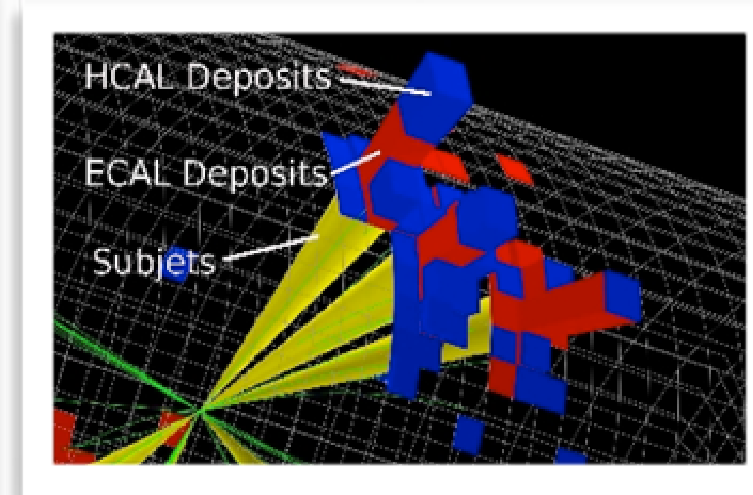
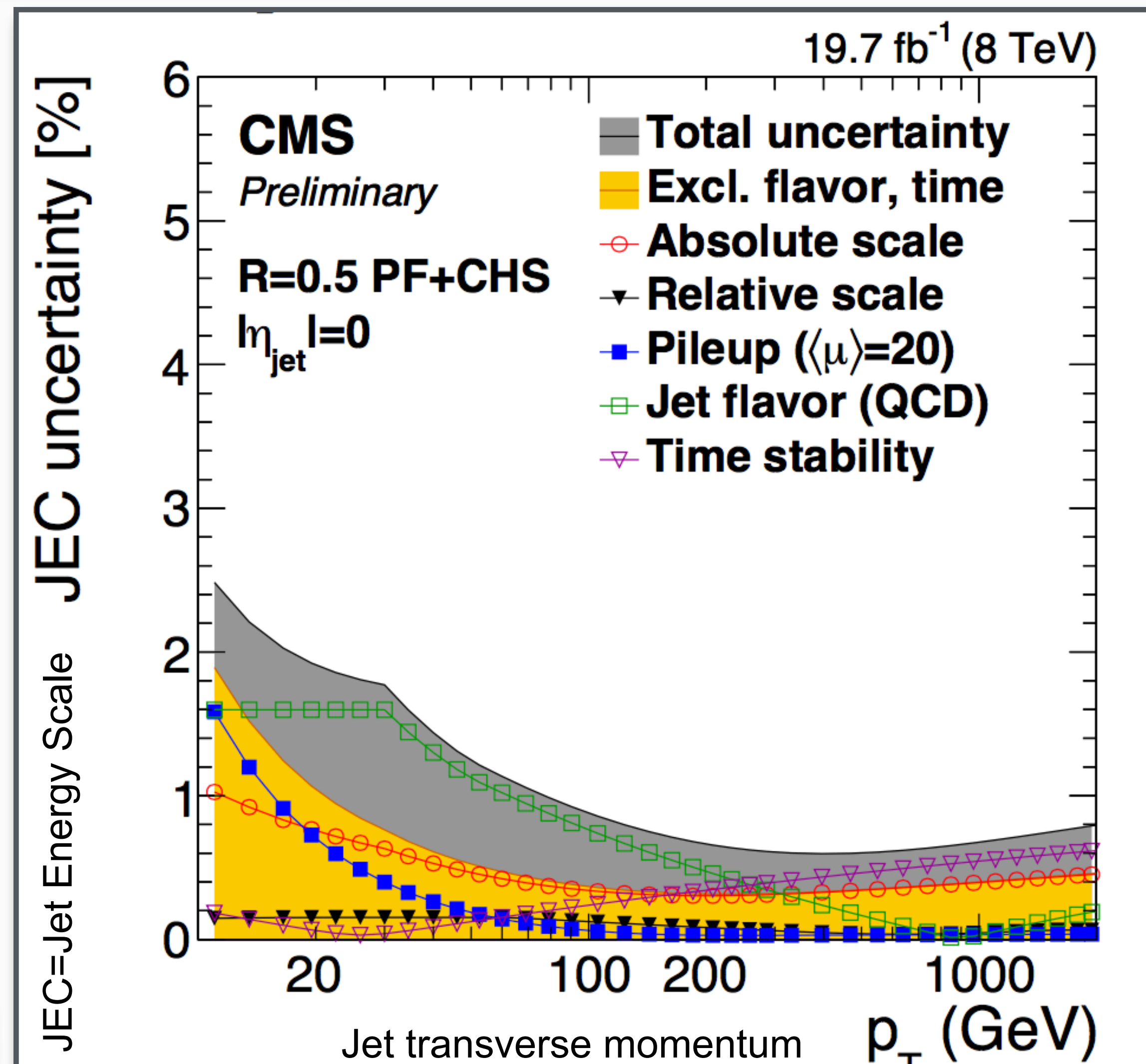


Impact on Jet Calibration





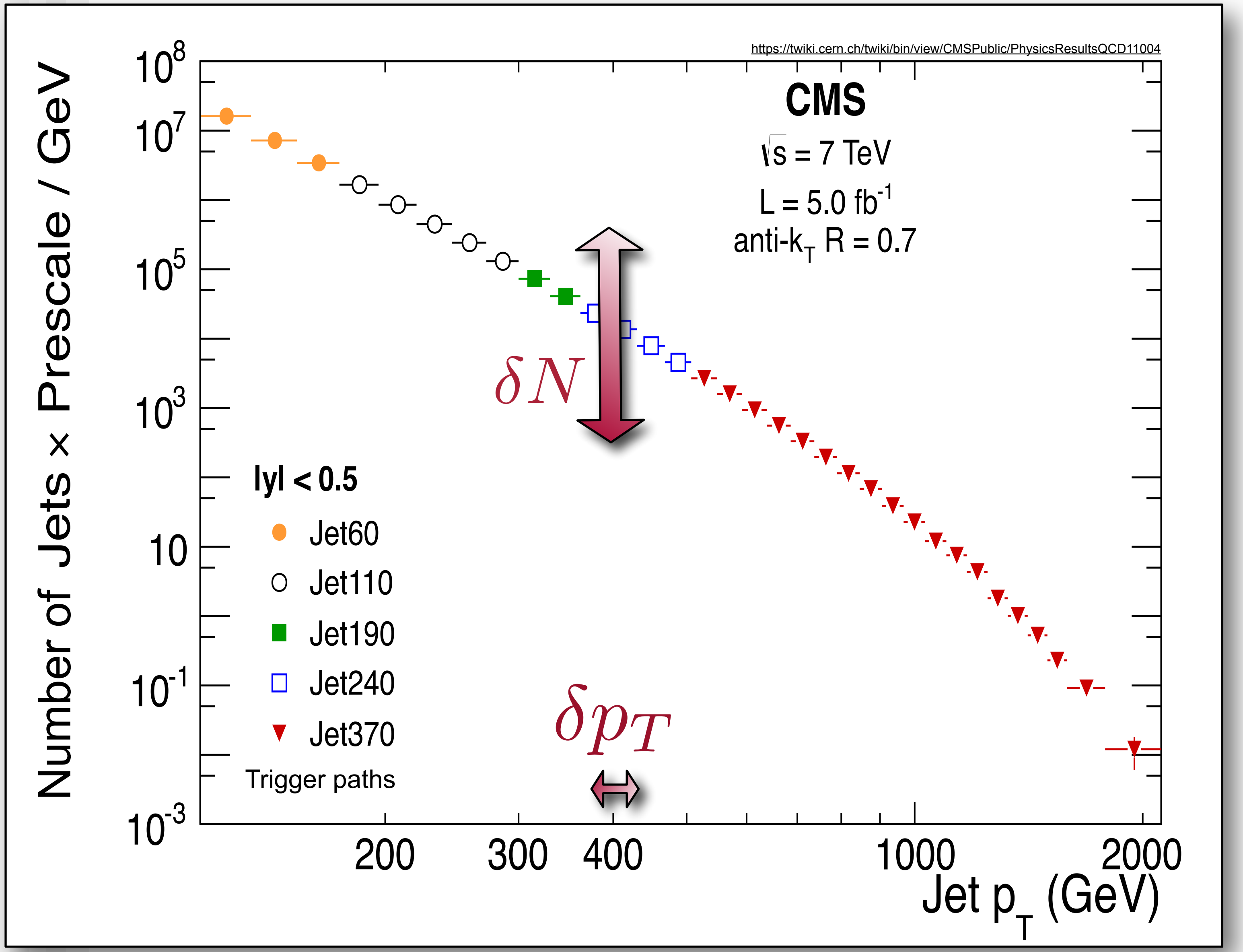




JES uncertainty <2% for most of the p_T range, JER about 10%

Jet energy calibration

- Question : how well do we know the calibration of the variable on the x-axis, eg. jet energy?
- A general problem for a very steeply falling spectrum!
- It makes a **big** difference if the jet energy scale uncertainty is 1%, 2% or 5%



$$\frac{d\sigma}{dp_T} \approx \text{const} \cdot p_T{}^{-n}$$

n large, eg. $n \approx 6$

relative uncertainties

$$\frac{\delta N}{N} \approx 6 \cdot \frac{\delta p_T}{p_T}$$

so beware:

eg. an uncertainty of **5%** on absolute energy scale (calibration)

➔ an uncertainty of **30%** (!) on the measured cross section

The Luminosity

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon\, L}$$

Two possible approaches

$$\sigma_{\mathrm{meas}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\varepsilon \;\; L}$$

invert the problem

$$L = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\epsilon \;\; \sigma_{\mathrm{theo}}}$$

Needs a very precisely calculable process, eg. W and Z production, as well as low exp. uncertainties

measure the luminosity from first principles

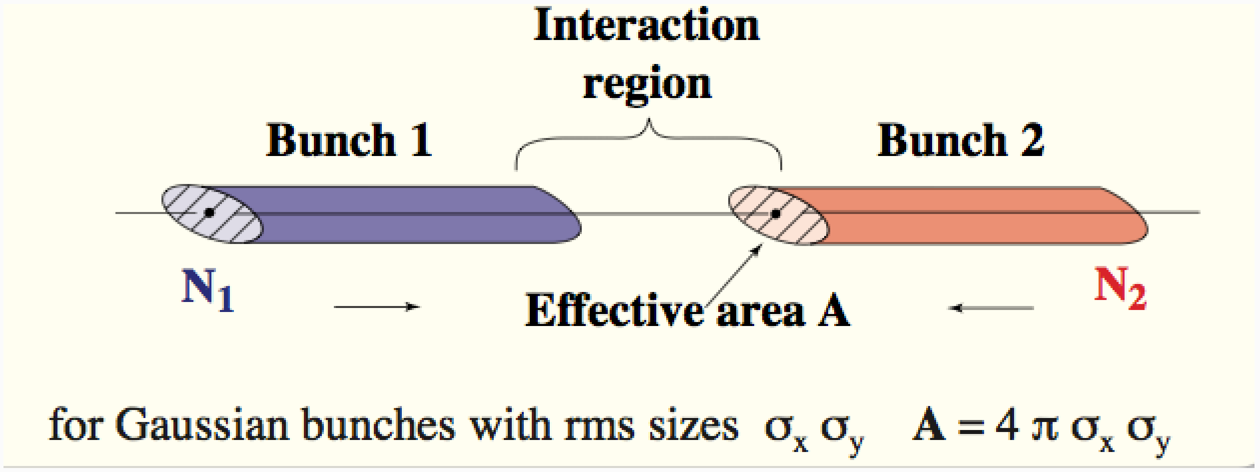
$$L = \frac{N_1 N_2 \nu_{\mathrm{orb}} N_b}{2\pi \sigma_{\mathrm{eff}}(x) \sigma_{\mathrm{eff}}(y)} \equiv \frac{\dot{N}}{\sigma}$$

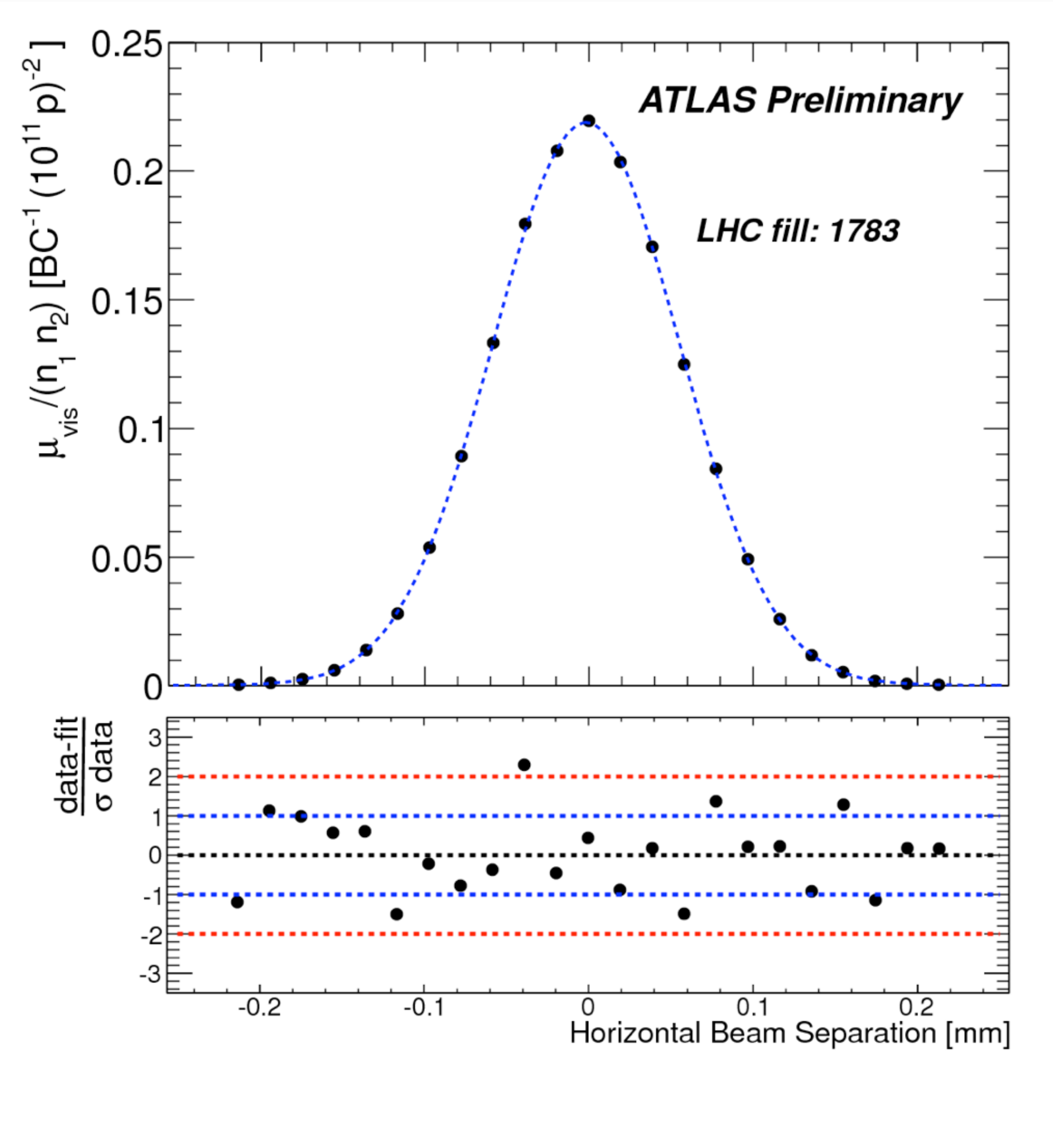
Have to measure:

- beam currents
- effective beam size --> Van der Meer scan !
- then, after absolute calibration:
  take stable process to measure evolution in time, eg. number of counts in forward calorimeters

Van der Meer scans

- Move the beams relative to each other and monitor the rate of some basic process, eg. MinBias triggers





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Uncertainty Source	$\delta\mathcal{L}/\mathcal{L}$
vdM Scan Calibration	3.4%
Afterglow Correction	0.2%
Long-term consistency	1.0%
μ Dependence	1.0%
Total	3.7%