

# QCD Uncertainties at the LHC



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- Outline:
- Minimum bias events
  - Jet production
  - Drell-Yan processes
  - Top quark production
  - Higgs in VBF channel
  - Higgs in photon channel

...just examples !

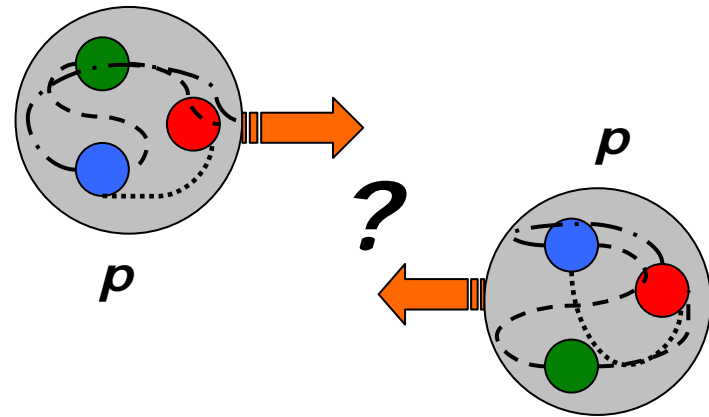
# LHC (Large Hadron Collider):

- p-p collisions at  $\sqrt{s} = 14\text{TeV}$
- bunch crossing every 25 ns

low-luminosity:  $L \approx 10^{33}\text{cm}^{-2}\text{s}^{-1}$   
( $L \approx 10\text{fb}^{-1}/\text{year}$ )

high-luminosity:  $L \approx 10^{34}\text{cm}^{-2}\text{s}^{-1}$   
( $L \approx 100\text{fb}^{-1}/\text{year}$ )

What do we expect from a proton-proton collision at a centre-of-mass energy of 14 TeV?



Process	$\sigma[\text{nb}] \approx \text{evts}/\text{sec}$
Jets, $E_T > 100\text{ GeV}$	$10^3$
2000 GeV	$10^{-4}$
$W^\pm \rightarrow e \nu_e$	20
$Z^0 \rightarrow e^+ e^-$	2
Photons $E_T > 60\text{ GeV}$	20
$\bar{c}c, \bar{b}b$ - Quarks	$10^7, 5 \cdot 10^5$
$\bar{t}t$ - Quarks	0.8

Production cross section and dynamics are largely controlled by QCD.

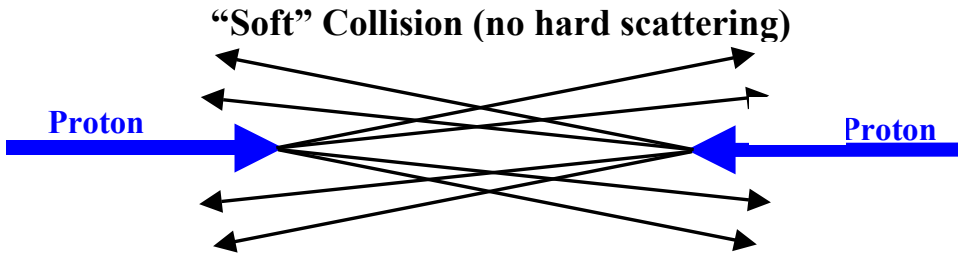
Mass reach up to  $\sim 5\text{ TeV}$

Test QCD predictions and perform precision measurements.

# Minimum Bias and Underlying Events

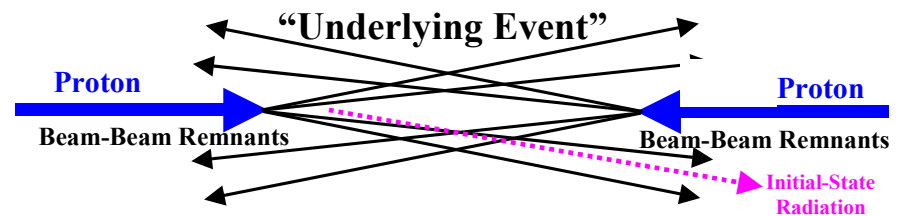
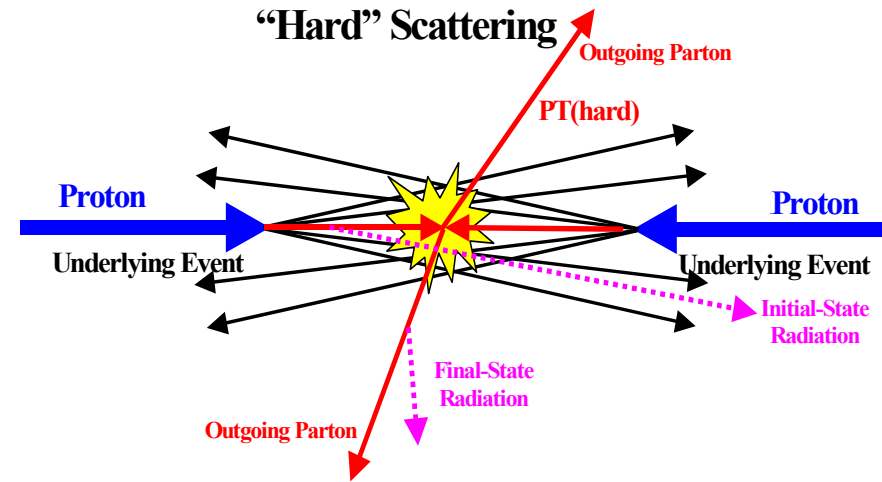
## Minimum bias (MB) event:

(more or less) soft hadron-hadron collisions  
At LHC ~40 of them in every event



## Underlying event (UE)

the rest of the event other than the hard scatter



MB not the same as UE !

Needs careful treatment,  
limits precision measurements,  
requires excellent modeling

# Models for Minimum Bias and Underlying Events

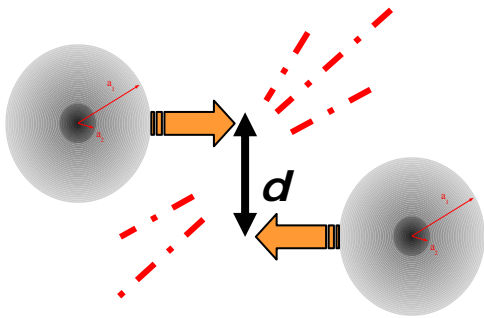
There will be a combination of “soft” (most of the time) and “hard” (occasionally) interactions. can have a **hard** component (parton-parton scattering) and a **soft** component (soft hadron-hadron collisions or remnants).

## PYTHIA

$$\sigma_{\text{int}} = \int_{\mathbf{p}_{t0}}^{s/4} \frac{d\sigma}{dp_t^2} dp_t^2$$

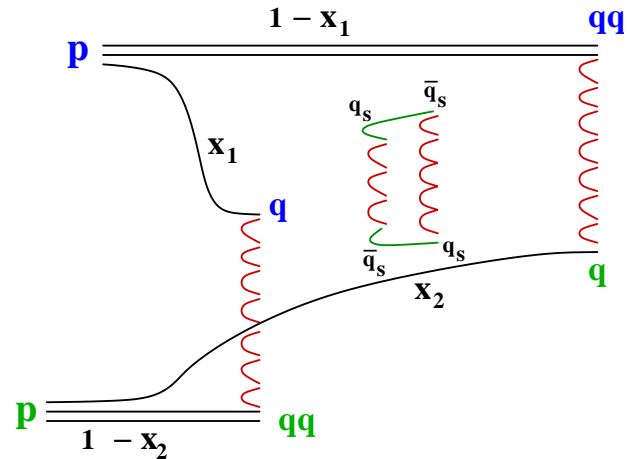
$$n \sim \sigma_{\text{int}}$$

$$\downarrow p_{t0} \quad \uparrow n$$



$\downarrow d$   $\uparrow$  probability of hard-scattering

## PHOJET



Multiple Pomeron exchanges

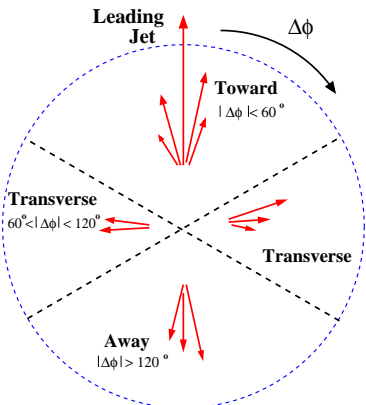
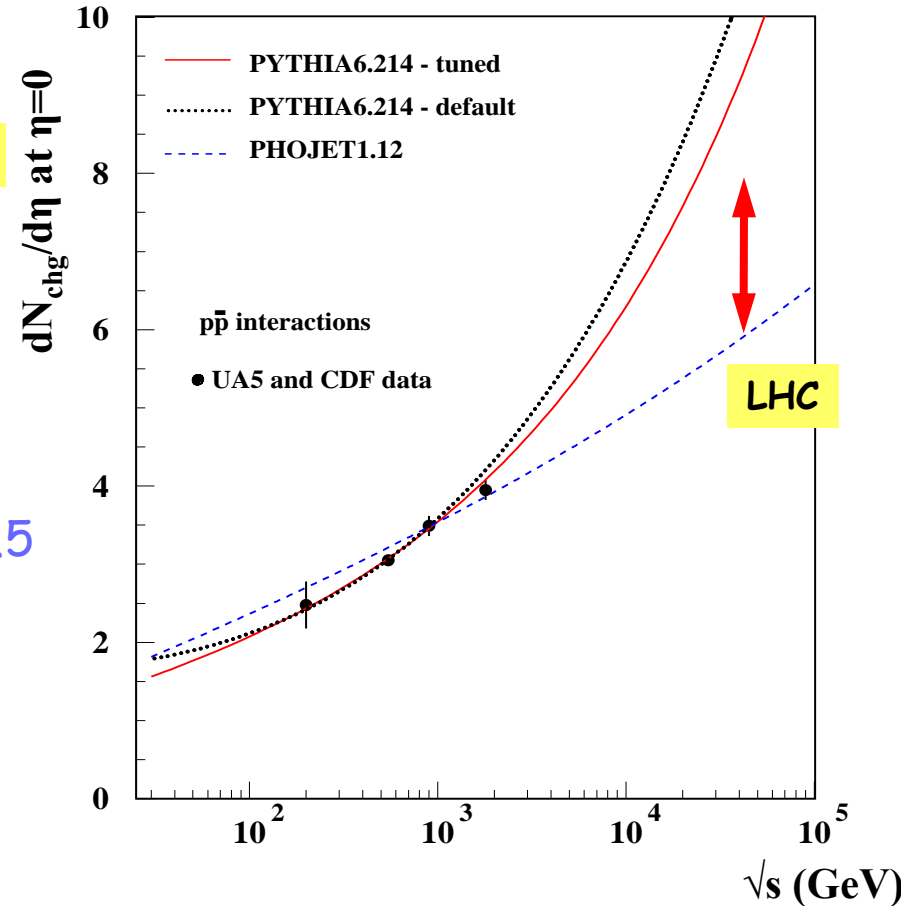
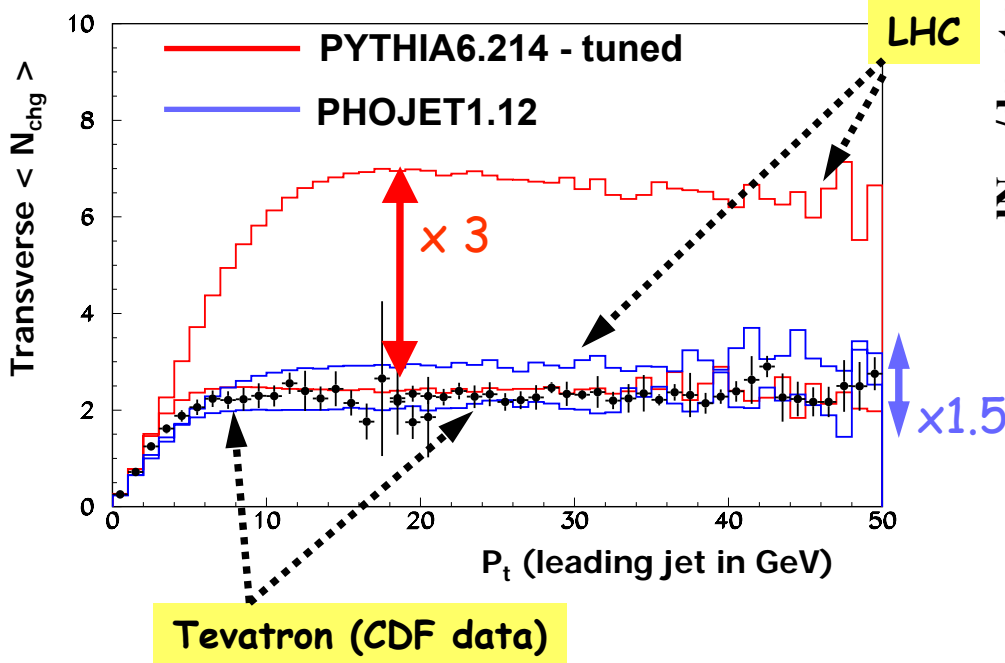
Implements ideas of **Dual Parton Model** for low- $p_T$  processes with **soft** and **semi-hard** particles

...more models and new ideas available: e.g. JIMMY etc

# Predictions for LHC for Underlying Events

Moraes, Buttar, Dawson  
(see also work of R. Field)

After comprehensive study and tuning:

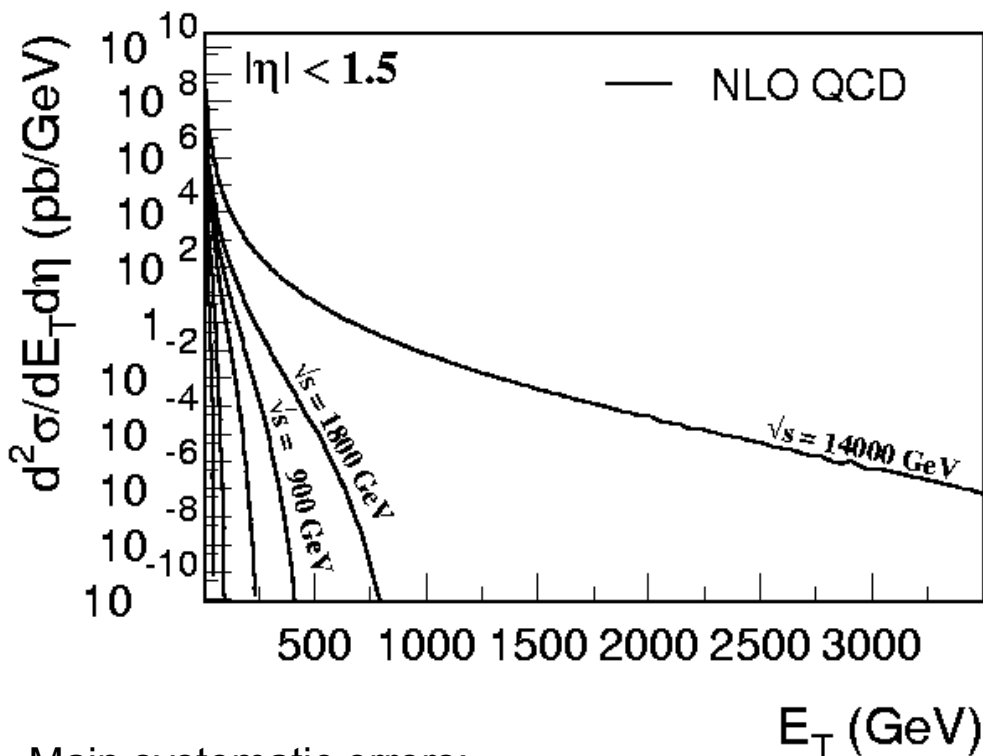


Agreement with CDF data, but different predictions in region transverse to the leading jet !

MB can be easily measured at LHC  
UI more difficult  
Model tuning can, however, only be successful if model are more or less correct

# Jet physics: Single Inclusive Cross-section

- test of pQCD in an energy regime never probed!
- first measurement to validate our understanding of pQCD at high momentum transfers
- $\alpha_s(M_Z)$  measurement with 10% accuracy (can be reduced by using the 3-jet to 2-jet production, combined Pdf /  $\alpha_s(M_Z)$  to be tried out)
- possible extraction of quark(x,  $Q^2$ ) and gluon (x,  $Q^2$ )



Main systematic errors:

- calorimeter response (jet energy scale),
- jet trigger efficiency,
- luminosity (dominant uncertainty  $\sim 5\%$ ),
- the underlying event.

$L = 30 \text{ fb}^{-1}$

Jet $E_T$	$N_{\text{events}}$
> 1 TeV	$4 \times 10^5$
> 2 TeV	$3 \times 10^3$
> 3 TeV	40

Typical jet trigger thresholds:

(with no prescale)

1 jet: 400 GeV

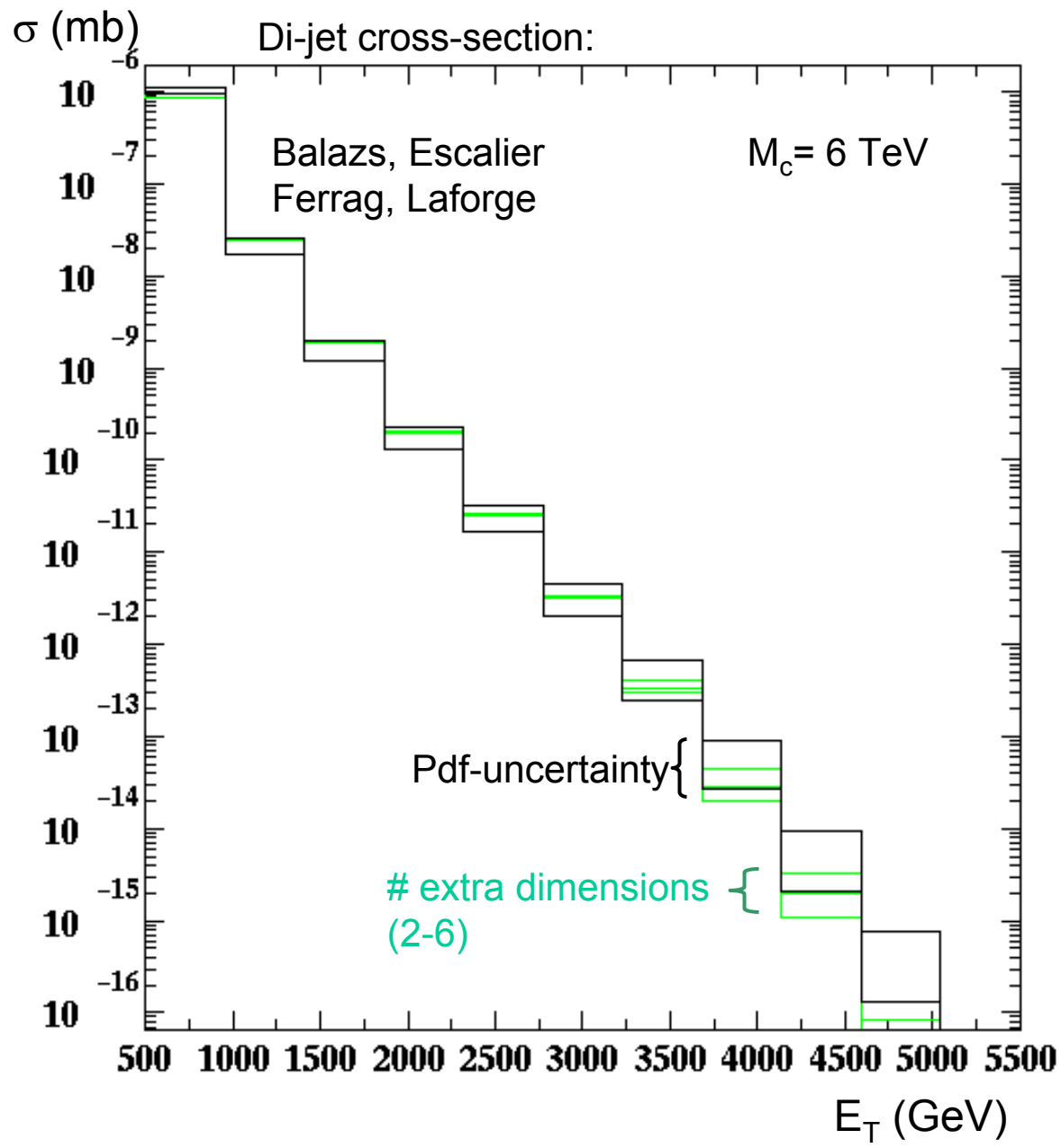
2 jet: 350 GeV

3 jet: 150 GeV

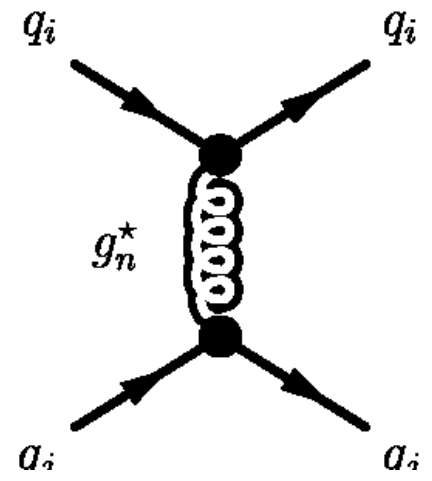
4 jet: 100 GeV

At the LHC the **statistical** uncertainties on the jet cross-section will be **small**.

# Example: QCD Uncertainty Masking new Physics



Assume:  
 extra space dimensions at TeV scale  
 modify energy dependence of  
 strong coupling via  
 virtual Kaluza-Klein state exchange

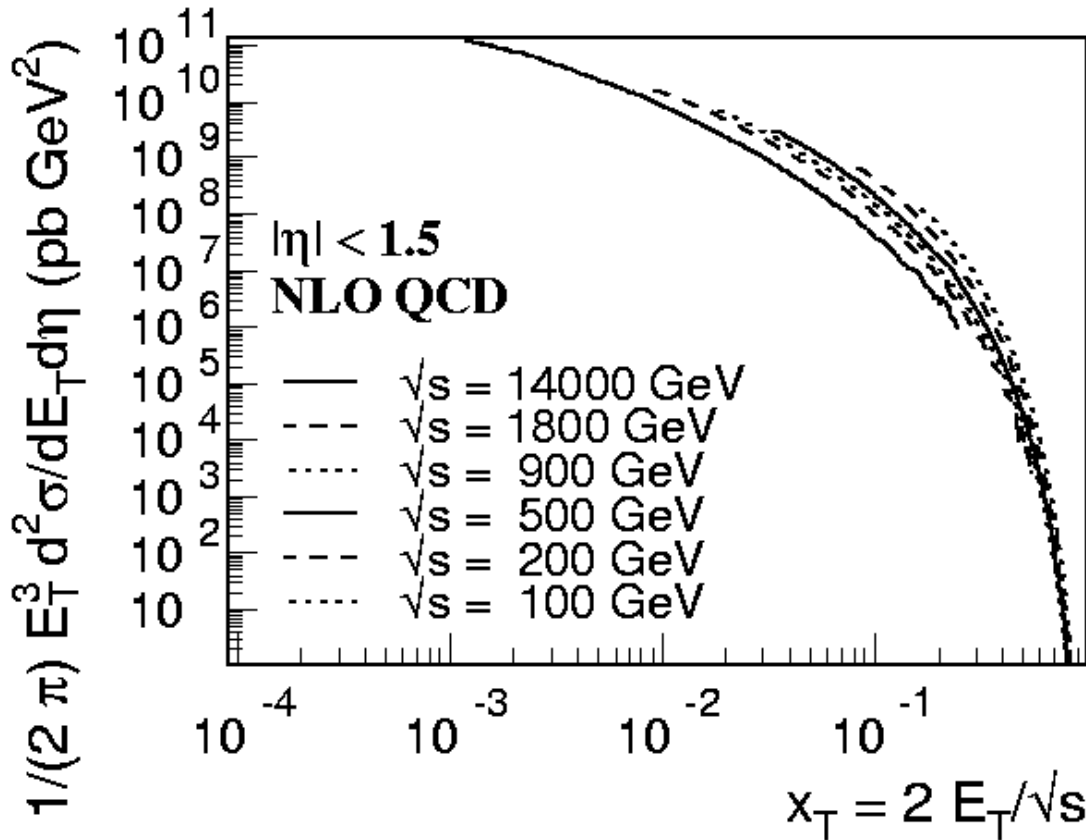


$M_c$  compactification scale

Present uncertainty on high-x gluon  
 decrease discovery reach from  
 $M_c = 5$  TeV to  $M_c = 2$  TeV !

# Jet physics: Single Inclusive Cross-section

Large momentum transfers and small-x !



Look at all possible processes simultaneously to avoid tuning away of new physics in one channel

Essentially all physics at LHC are connected to the interactions of quarks and gluons  
→ precise knowledge needed for:  
W/Top-mass measurement,  
Higgs cross-section,  
search for contact interaction etc.

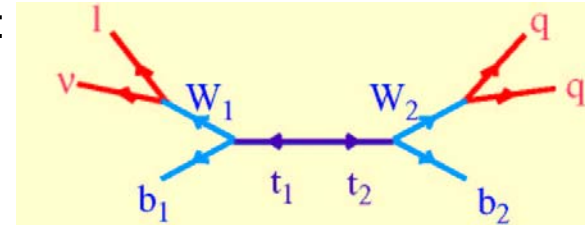
Accurate measurements of SM cross-sections at the LHC can constrain the parton densities  
→ sub-group within HERA-LHC workshop to work-out experimental program

# Multi-jets/Multi-particles

LHC: large centre-of-mass energy  $\rightarrow$  large phase space, many particles in the final state

Multi-jet/particle production is important for several physics studies:

- $t\bar{t}$  production with hadronic final state
- Higgs production in association with  $t\bar{t}$  and  $b\bar{b}$
- Search for R-parity violating SUSY (8 – 12 jets).



$\rightarrow$  Need to go beyond PYTHIA/HERWIG approach !

Many important progress over past few years:

## N-parton/particle ME event generators:

automatic LO-ME generation up to  $2 \rightarrow 6$  processes + phase space integration, PS interface  
e.g SHERPA, MADEVENT etc.

## NLO parton level generators:

$2 \rightarrow 2$ : for most processes, see e.g. MCFM, MNR, NLOJET++

$2 \rightarrow 3$ : first processes available:  $pp \rightarrow 3$  jets,  $pp \rightarrow W/Z + 2$  jets,  $pp \rightarrow \gamma\gamma$  jets,  $pp \rightarrow t\bar{t}H$ ,  $pp \rightarrow t\bar{t}$  jet

...ideas for automated calculations upcoming !

## MC@NLO: full event generator using NLO ME/PS/hadronisation model

Hard emissions are treated with NLO ME while soft/collinear emissions by PS  
HQ, Higgs, Drell-Yan, W/Z-pairs ...extendable

## NNLO:

first results start being available for

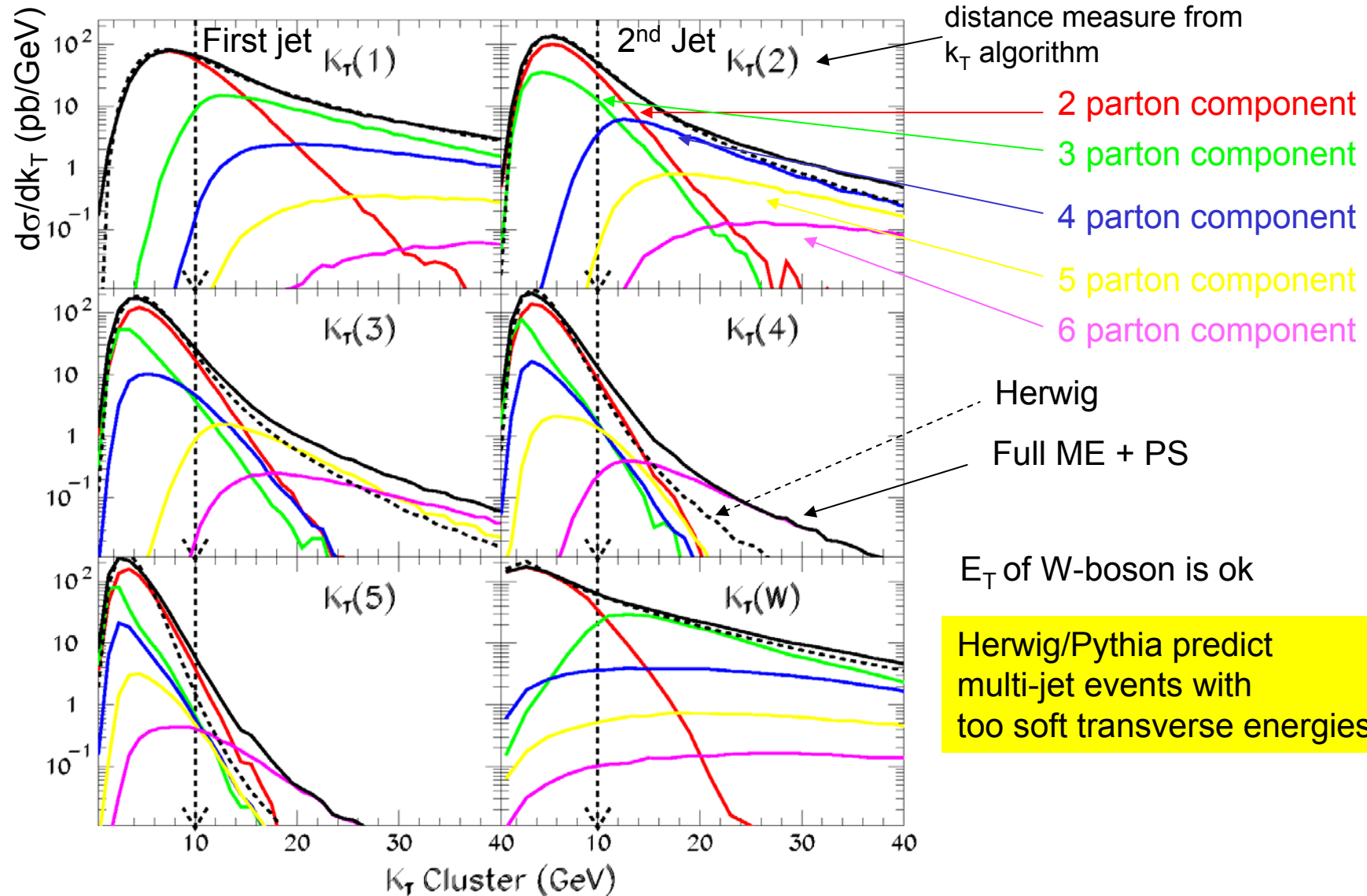
$\sigma_{\text{tot}}$  and rapidity distributions of Higgs and Drell-Yan

# Matching n-Jet ME and PS

Example: Richardson/Mrenna 2003

$$p\bar{p} \rightarrow W^+ + X \quad \sqrt{s} = 1.96 \text{ TeV}$$

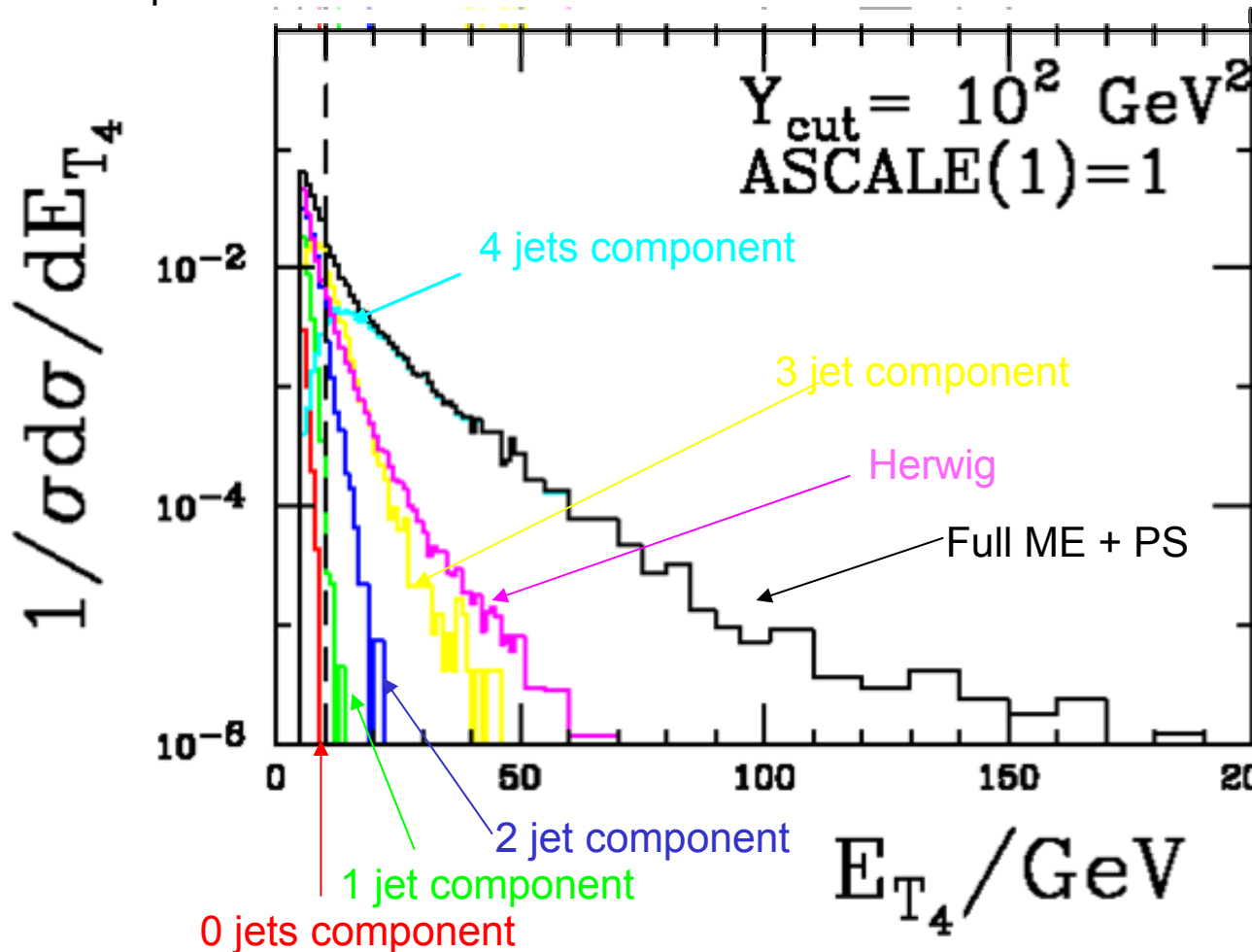
HERWIG-PS (hadron level)



# Mult-Jet Production at LHC

$$pp \rightarrow W^+ + X \quad \sqrt{s} = 14 \text{ TeV}$$

Example: Richardson 2003



Are the HERWIG/PYTHIA estimates for finding SUSY in multi-jet channels ok ?

# Drell-Yan Processes

Huge statistical samples & clean experimental channel. ( e,  $\mu$  channels! )

## W and Z production

$\sim 10^5$  events containing W ( $p_T^W > 400$  GeV)

$\sim 10^4$  events containing Z ( $p_T^Z > 400$  GeV)

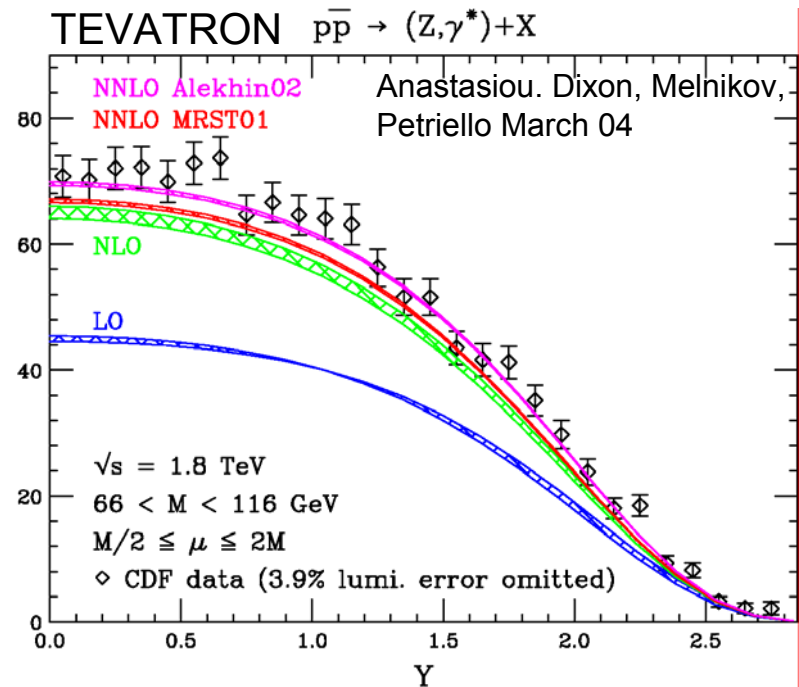
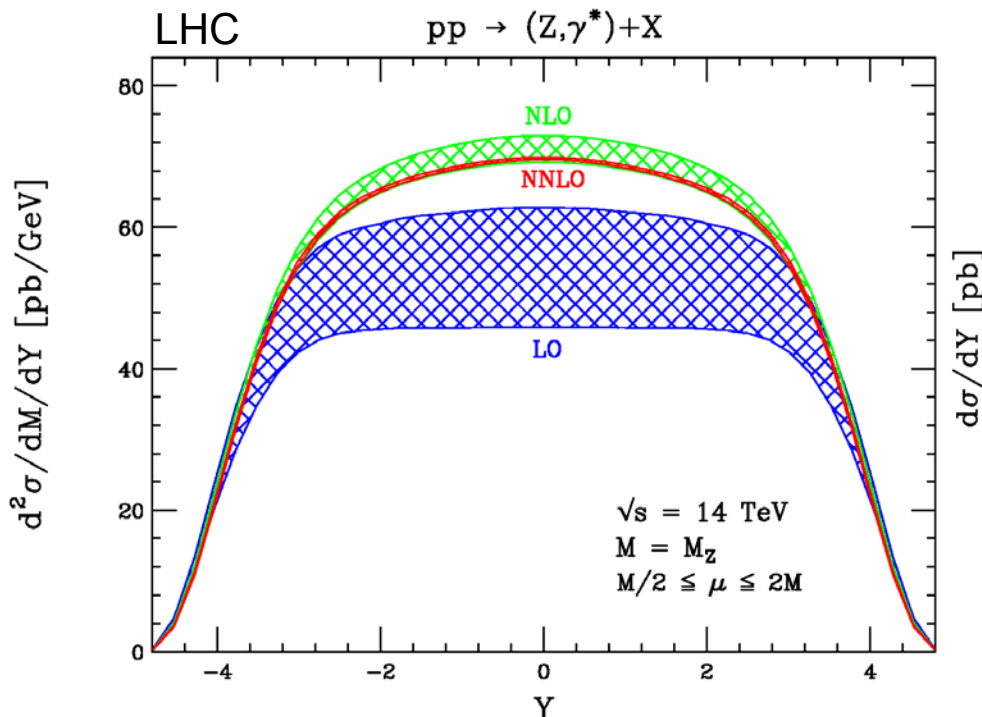
NNLO rapidity distribution recently completed !

for  $\mathcal{L} = 30\text{fb}^{-1}$

## DY production of lepton pairs:

$m_{\mu\mu} > 400$  GeV:  $10^4$  events (  $|\eta| > 2.5$  )

$Q^2 > 1.6 \cdot 10^5 \text{ GeV}^2$      $2.3 \cdot 10^{-3} < x < 0.34$



Scale dependence for W/Z-production below 1% in NNLO

Shape of rapidity distribution does not change  $\rightarrow$  e.g. MC@NLO + k-factor could be used in exp.

## “Standard candles” at LHC:

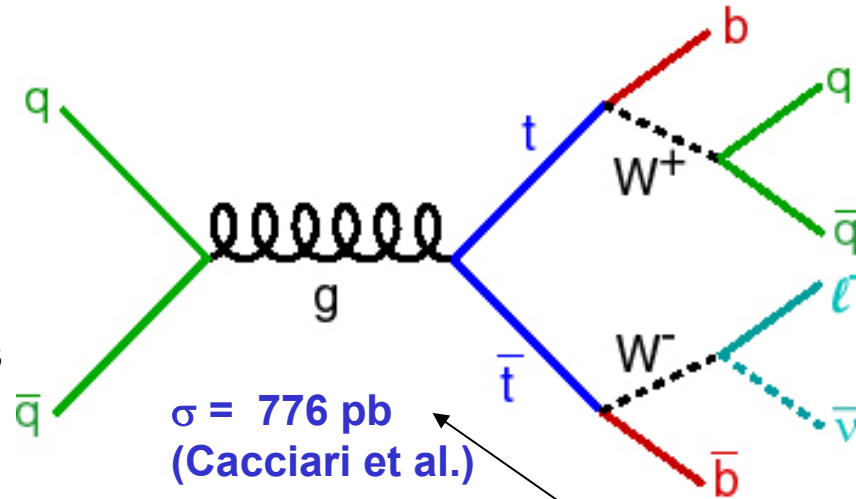
- Luminosity
- detector calibration
- constrain quark and anti-quark densities in the proton.

# Top Quark Production

## Interest in Top-Quarks:

- Fits into third generation – CKM
- Large mass interesting in itself  
...and close to EWBS scale !
- Heavy enough to decay to exotics
- Serious background in many searches

8 Million Events/Year !



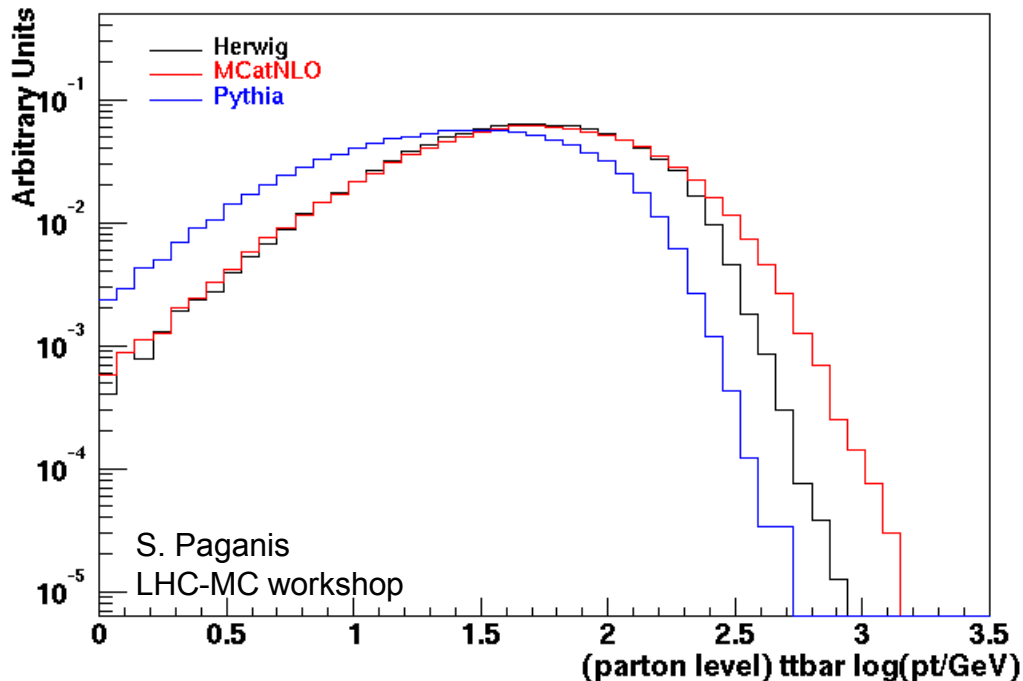
## Uncertainties:

$\pm 12\%$  from ren. and fact. scale

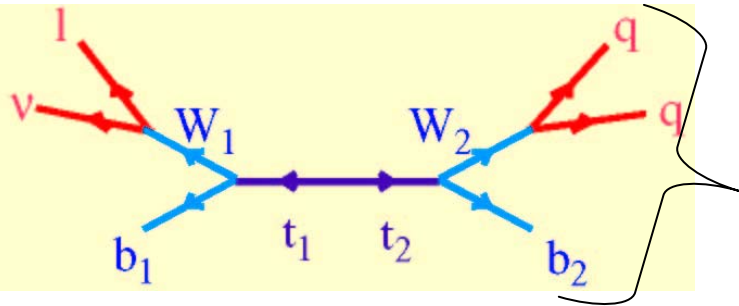
$\pm 5\%$  from pdf's

- Large phase space for QCD radiation
- Needs proper modeling with ME:  
hard emissions are correctly treated
- Pythia disagrees with HERWIG

tt system (recoil)  $p_t$  distribution



# Top Quark Mass Reconstruction



## Selection:

1 isolated lepton,  $p_T > 20$  GeV,  $|\eta| < 2.5$

$p_{T\text{miss}} > 20$  GeV

$\geq 4$  jets with  $p_T > 40$  GeV,  $|\eta| < 2.5$

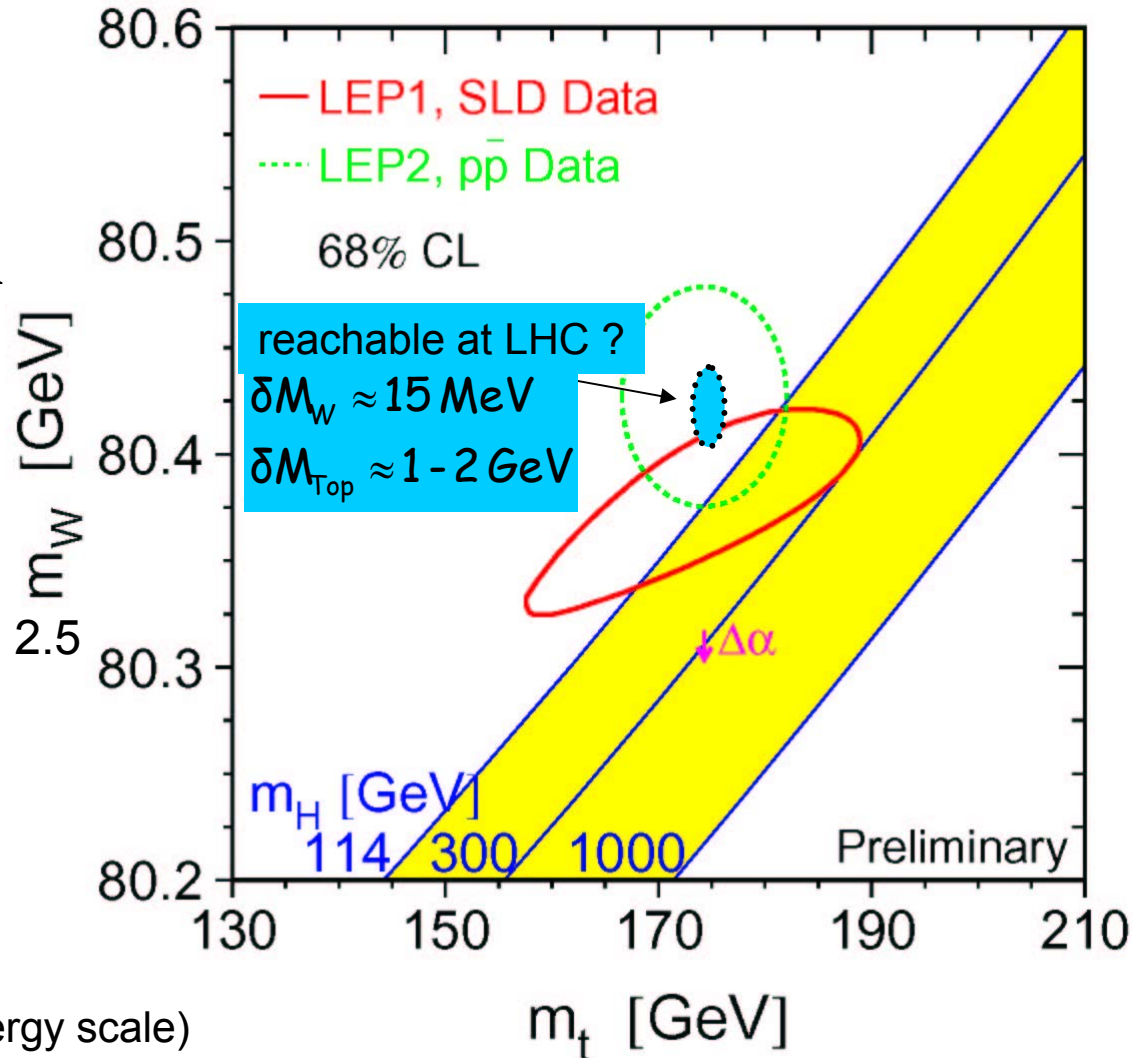
$\geq 2$  jets with b-tag

Expect  $\sim 30\text{k}$  signal events/year

Goal very challenging for detector (energy scale) and model uncertainties:

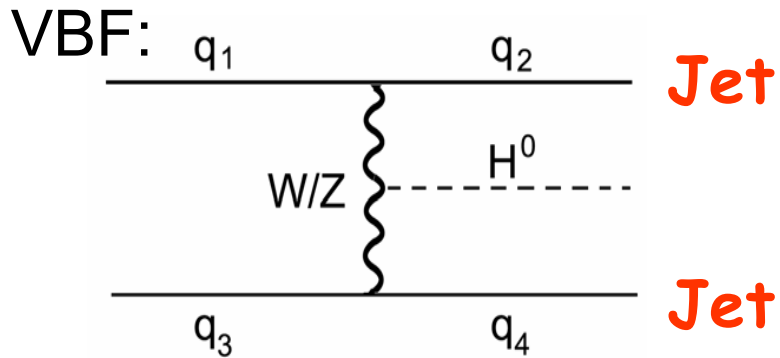
One of the largest uncertainty estimates from final state QCD radiation:

→ need good models to get small error

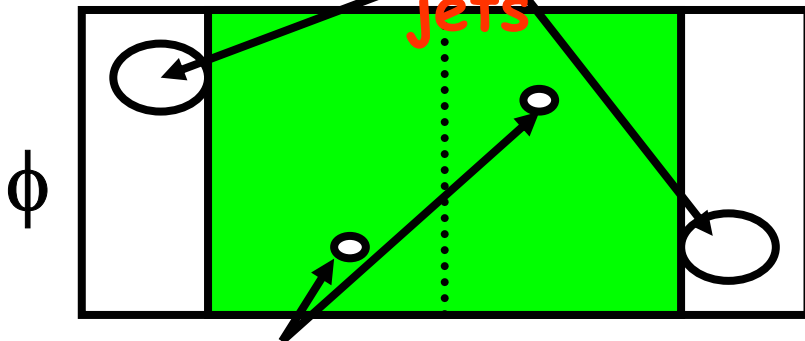


Chances for ruling out the SM !

# Low Mass Higgs via Vector Boson Fusion

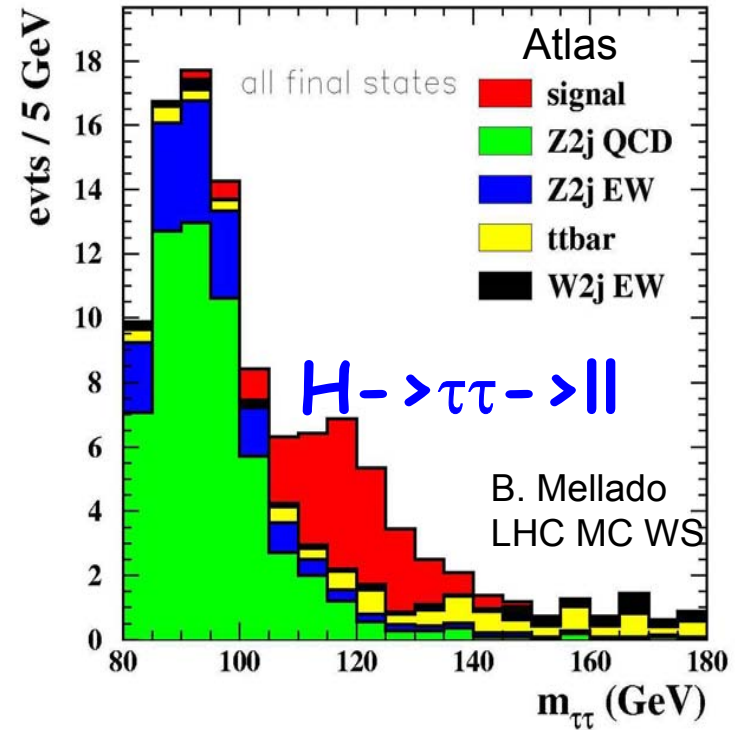


**Forward jets**



**Higgs Decay  $\eta$**

- Two high  $P_T$  jets with large  $d\eta$  separation
- Strong discovery potential for low Higgs mass
- VBF 20% of  $\sigma$  at  $M_H=120$  GeV
- Can measure Higgs couplings
- Good for invisible decays



No narrow resonances

Knowledge of SM background shapes crucial

→ needs good understanding of QCD radiation

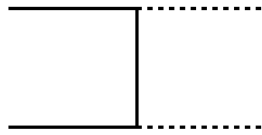
for W/Z/Top events:

- in forward region (tagging jets)
- in central region (jet veto)

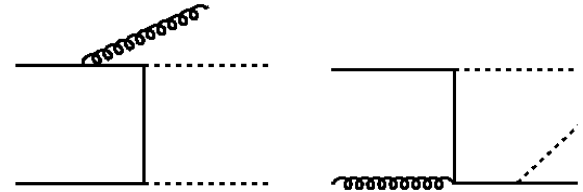
# Low Mass Higgs in Photon Channel

Background calculations:

- DIPHOX:

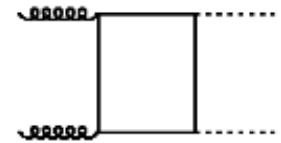


Higher orders +  
fragmentation effects

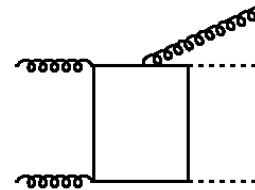


Binoth, Guilet,  
Pilon, Werlen

$gg \rightarrow \gamma\gamma$  through Box has similar rate  
(order  $\alpha^2\alpha_s^2$  but enhanced by pdf's)



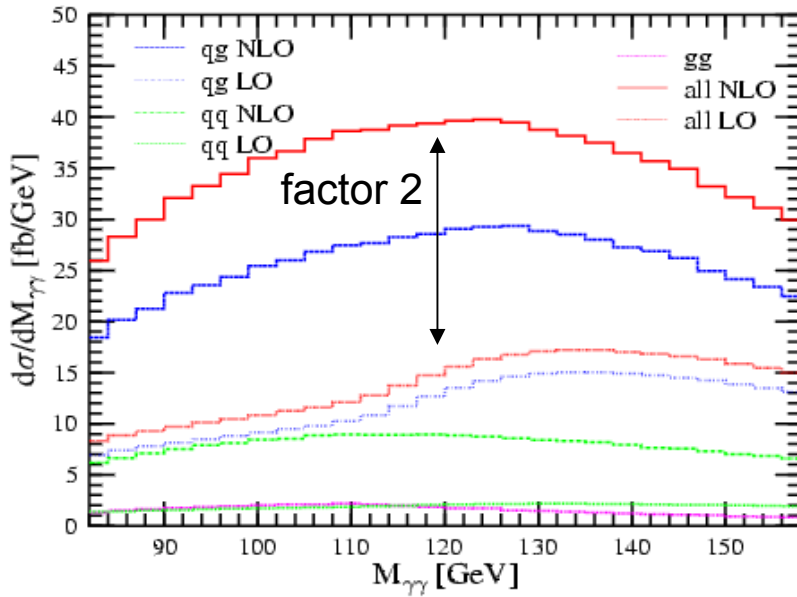
- Analytical calculation by Bern, Dixon, Schmidt  
for NLO contributions to box



+ extra loop

V. Del Duca et al.:

$p p \rightarrow \gamma\gamma + \text{jet}, E_{\text{cm}} = 14 \text{ TeV}$



Cut on  $P_T(\text{pair}) \Rightarrow$  improves S/B (by  $\sim 3-5$ )  
worse  $S/\sqrt{B}$  (by  $\sim 0.6$ )

$P_T(\gamma) > 40 \text{ GeV}, P_T(\text{jet}) > 40 \text{ GeV},$   
Isolation in cone with  $R=0.4$

NLO changes the shape !!!

No universal K-factor

(is large and depends on isolation cut)

# Conclusions

The proton gives us access to the highest possible energy, but is a rather complicated object

In 2007 LHC will collide protons with a centre-of-mass energy of 7 TeV !

To explore full potential of new energy frontier need to prepare:

- good detectors
- good models and tools and theory calculations
- program to calibrate detectors and to validate our understanding of SM processes
- many possibilities to squeeze present uncertainties...

I have only given some examples.