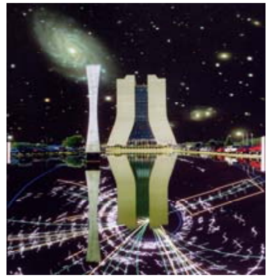
SM Results from the Tevatron & Prospects



M. Martínez-Pérez

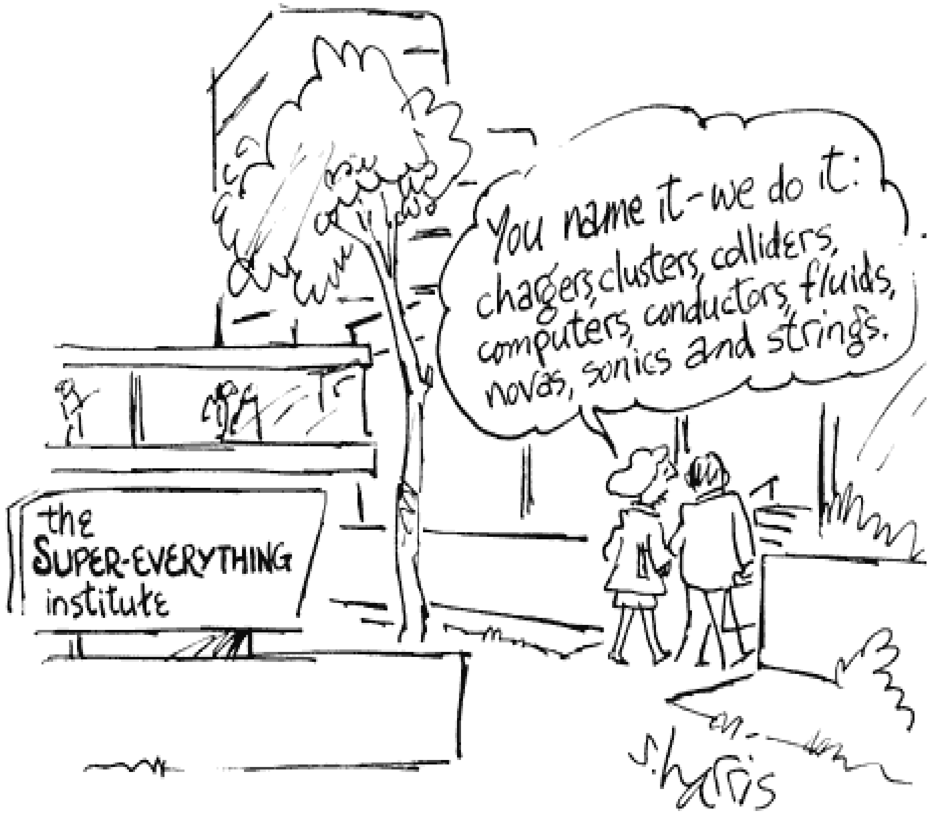
ICREA/IFAE-Barcelona

Results from CDF & D0 Collaborations

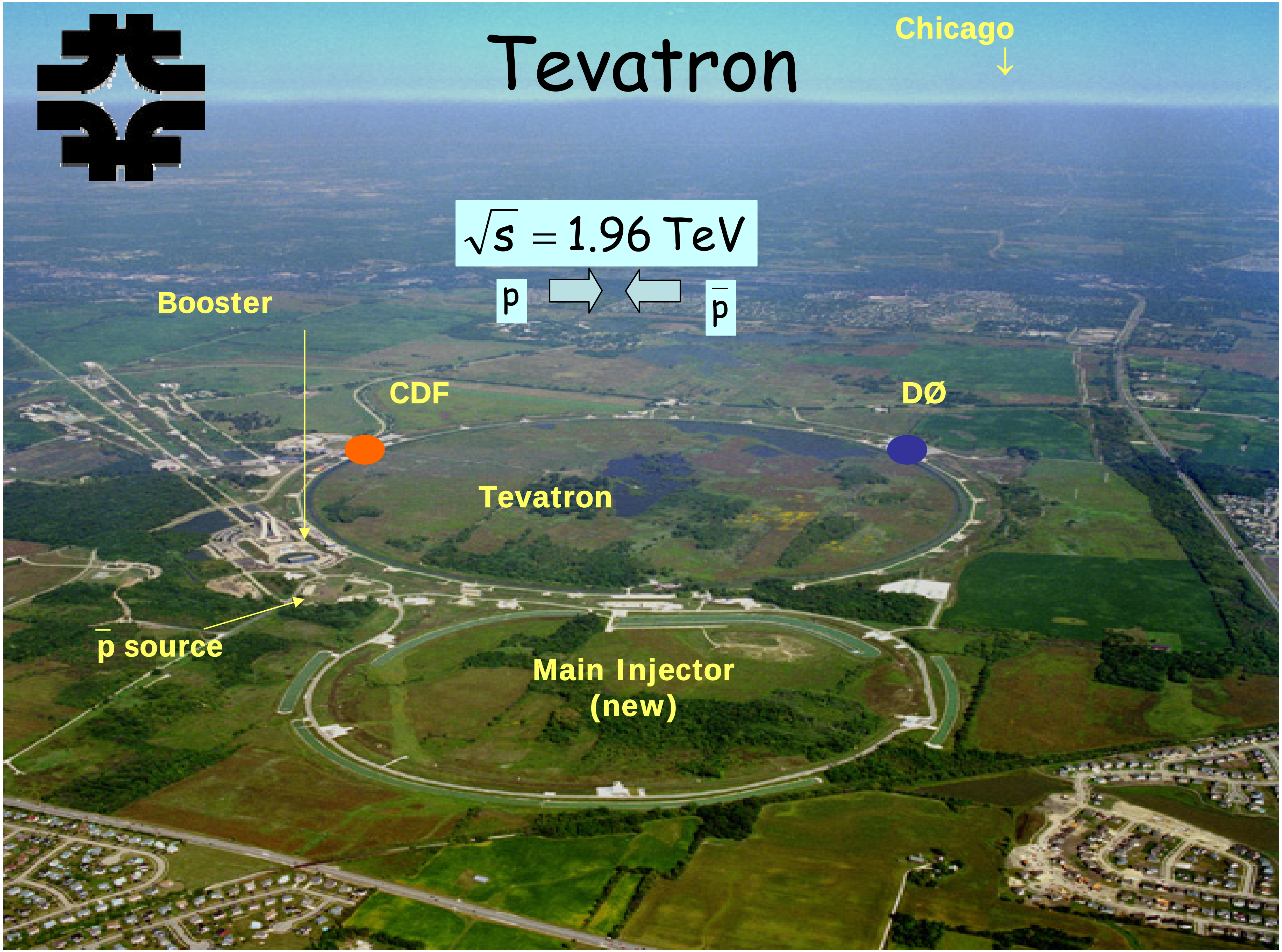
Lisbon, June 4th 2008

Outline

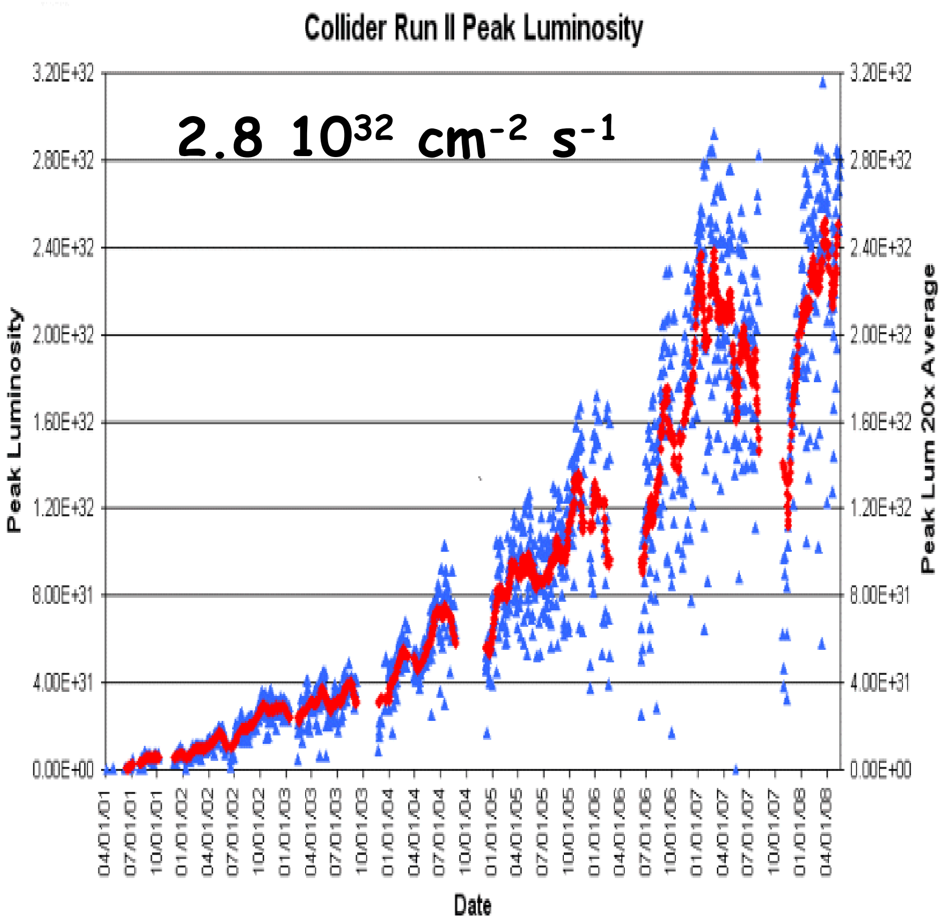
- Tevatron, CDF/D0
- QCD at large P_T
  - Jets
  - Underlying Event
  - Prompt Photons
- Drell-Yan
  - Cross Sections
  - W mass & width
  - Charge Asymmetry
  - W/Z+jets
- Top Physics
  - ttbar Cross Section
  - Top Mass
- Diboson Physics
- SM Higgs Searches
- Prospects for the first LHC data
- Final Remarks

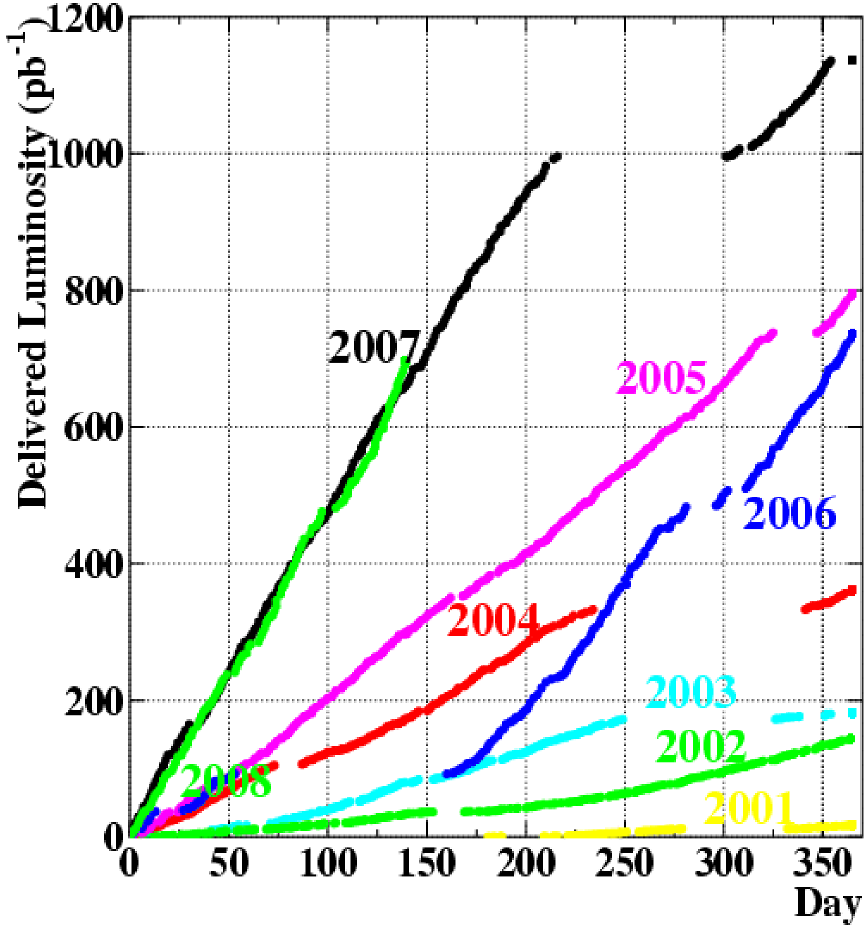


Not covered in this talk
- B-Physics / HF Jets
- Diffraction
- Single Top/Top Properties
- ……..


Tevatron
Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
$\bar{p}$ source
Main Injector
(new)

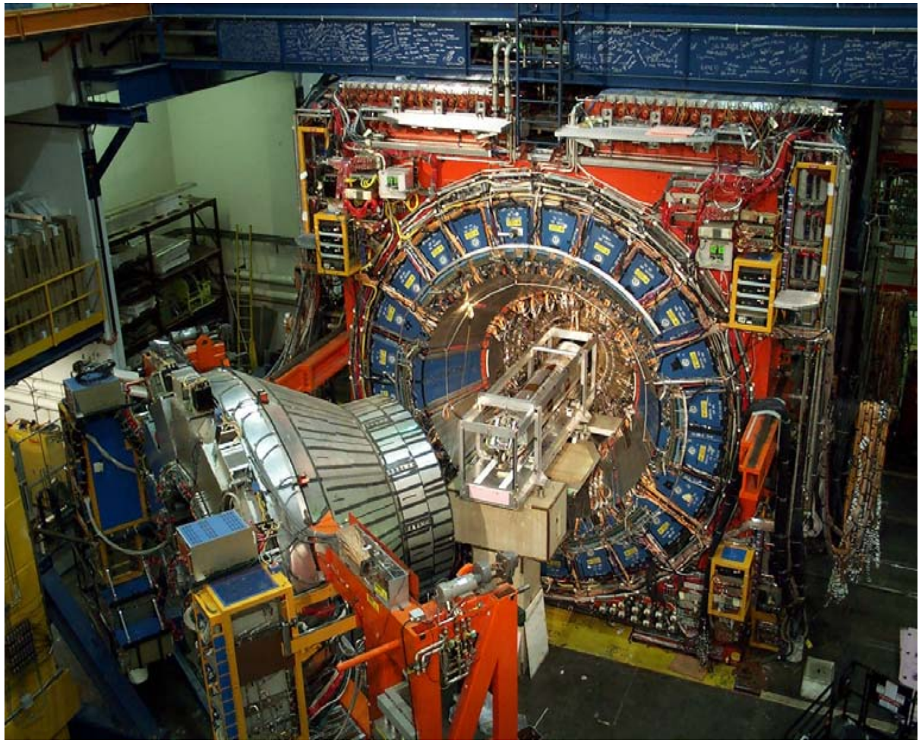
Tevatron Performance





Tevatron delivered > 4 fb^{-1}
(6-7 fb^{-1} expected by end FY09)

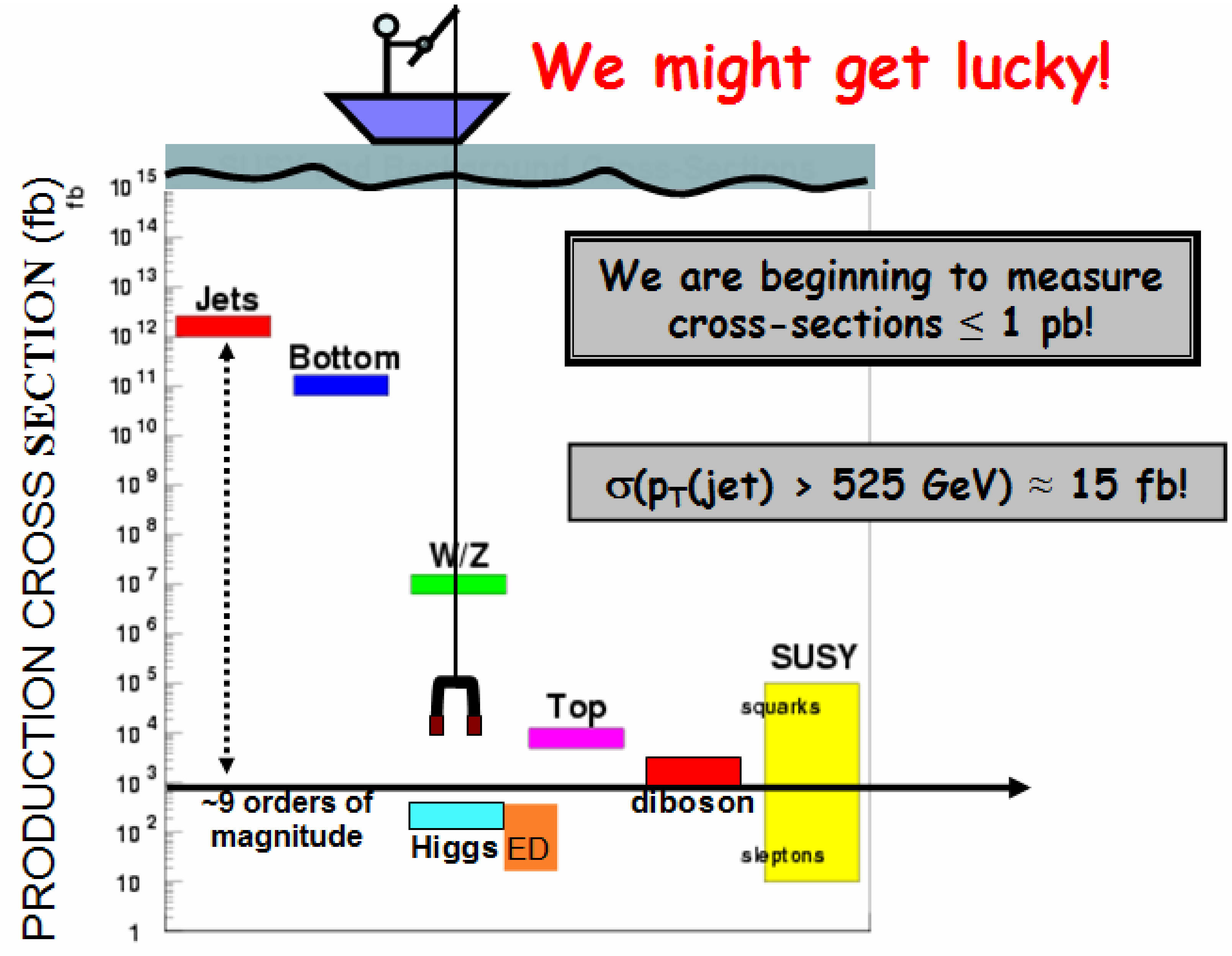
CDF & D0 Detectors



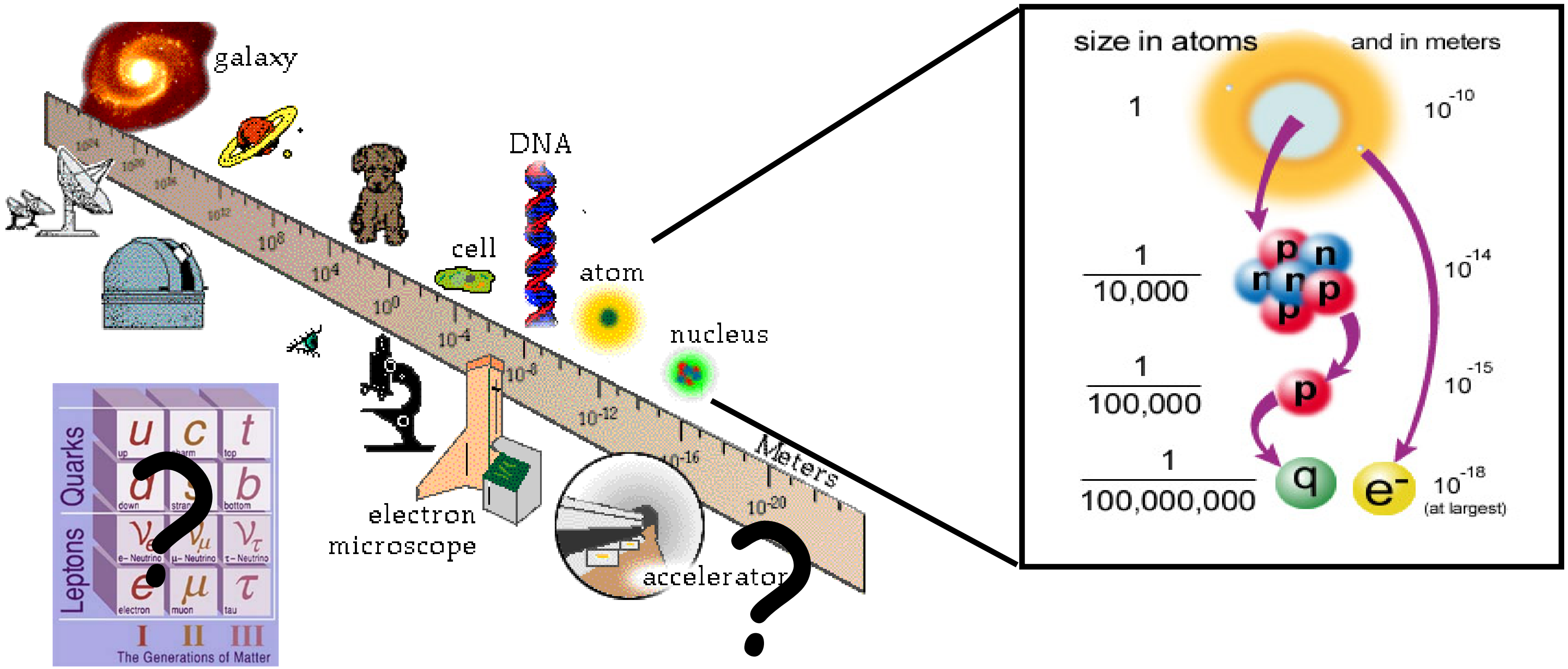
CDF & DØ operating well and recording physics quality data with very high efficiency (~85%)

Both experiments have already collected > 3.2 fb-1 on tape

Tevatron (SM) Physics

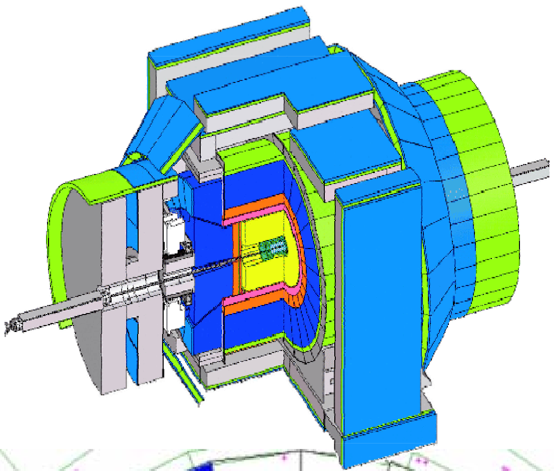


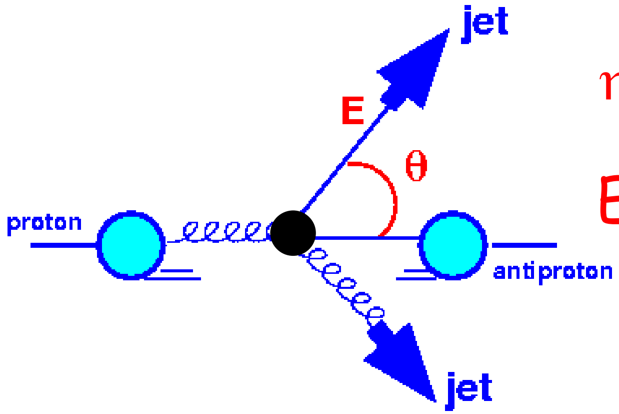
The Structure of Matter
(Jets & Compositeness)



Jets at Hadron Colliders probe distances down to 10^{-19}m $\Rightarrow$ QCD...

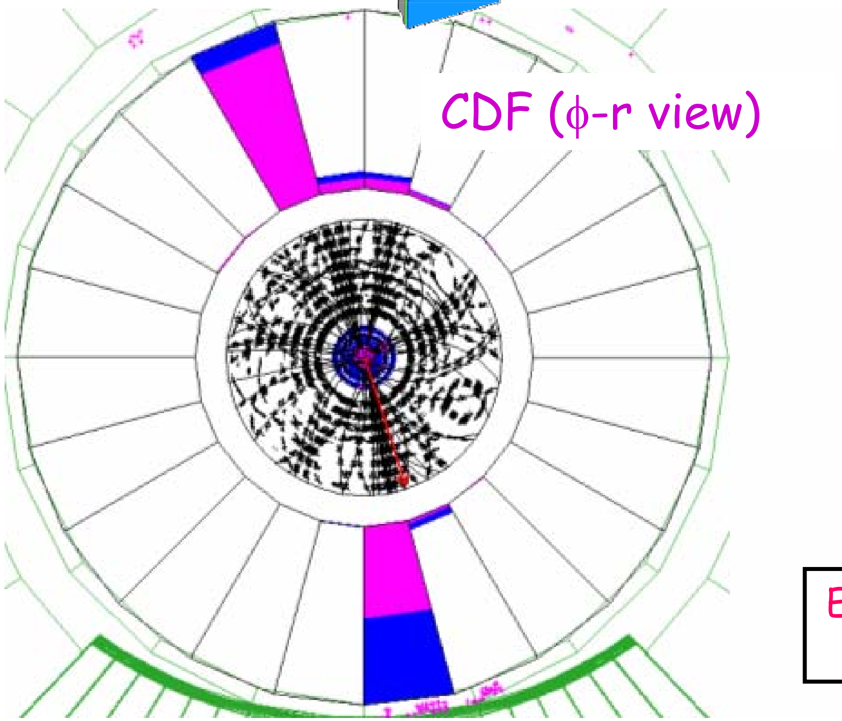
High P_T Jet Event in CDF



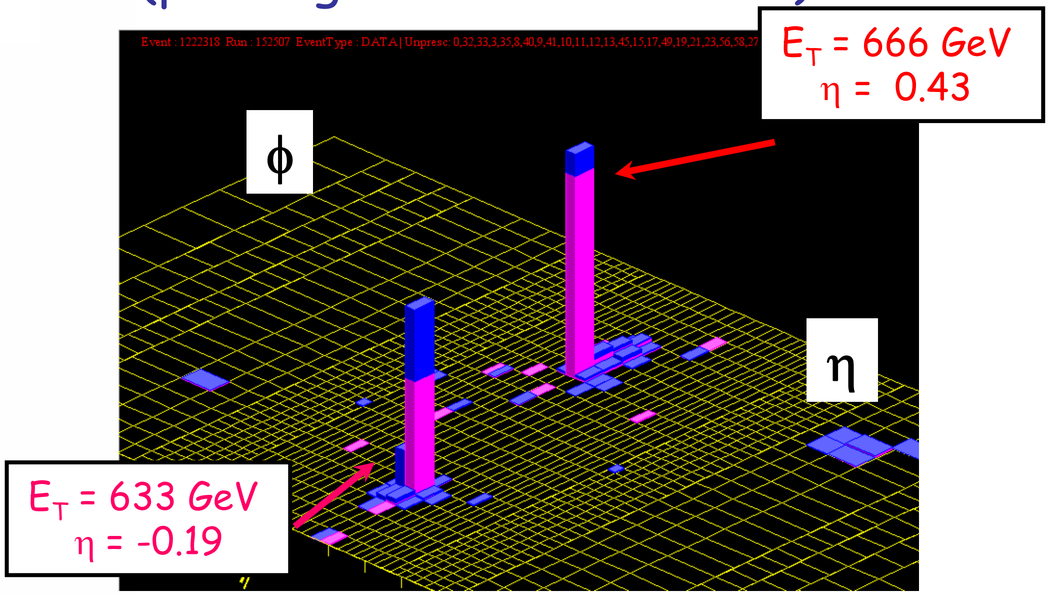


$$\eta = -\ln(\tan\frac{\theta}{2})$$

$$E_T = E\sin\theta$$

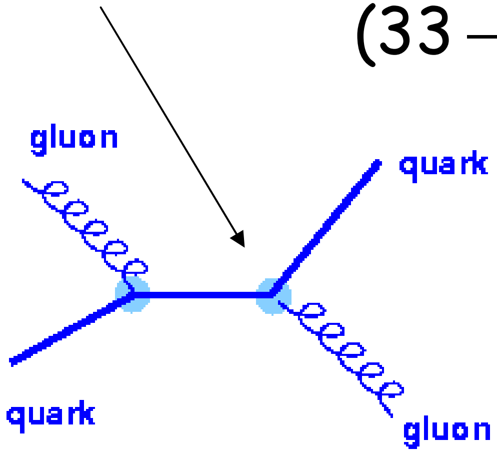


Dijet Mass = 1.36 TeV
(probing distance ~10^{-19} m)

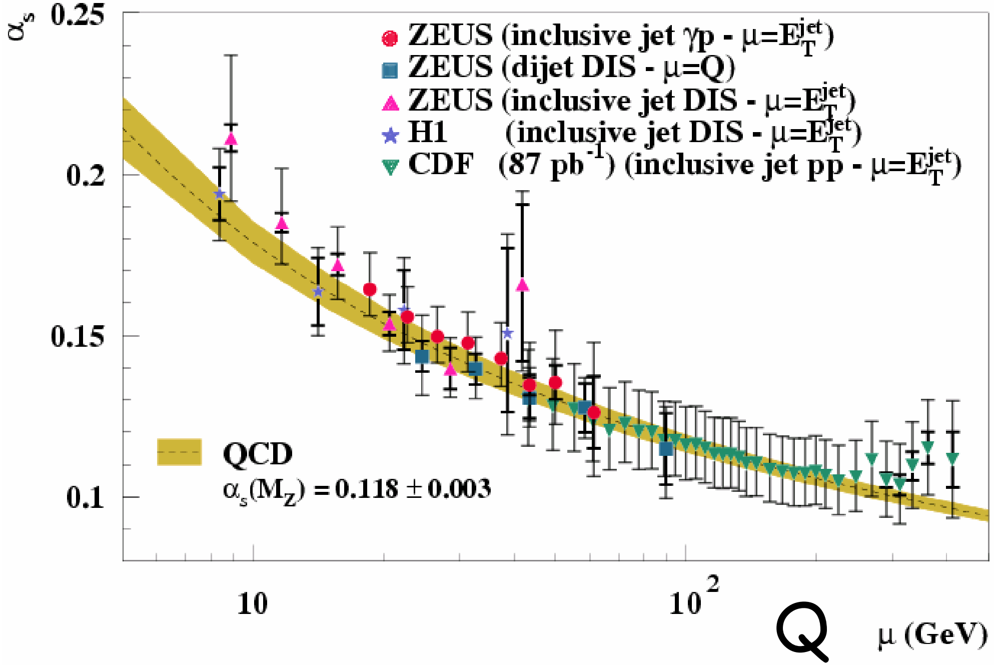


QCD : Asymptotic freedom & Confinement

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln \frac{Q^2}{\Lambda^2_{QCD}}}$$

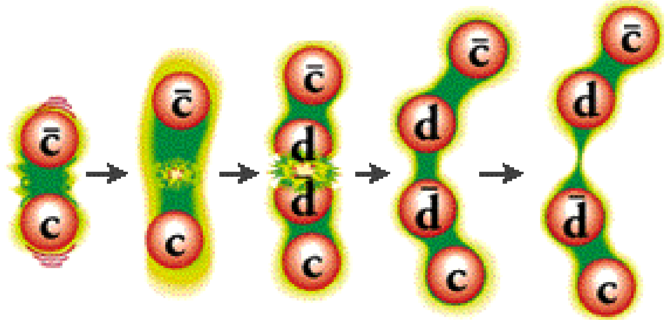


$$\hat{\sigma}_{qg \to qg}$$



At high Q (short distances) perturbation theory can be used to compute partonic cross sections

Quarks confined inside hadrons

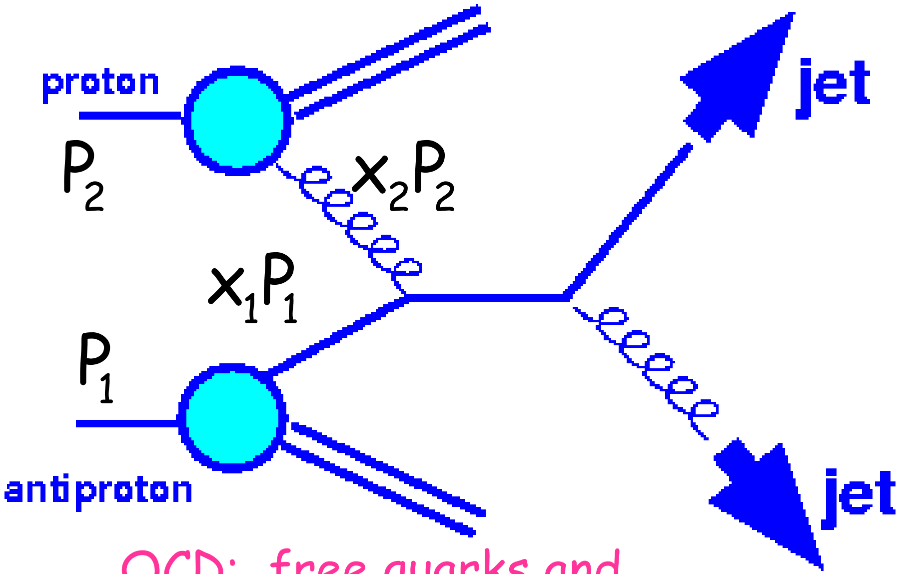


At low Q (large distances) pQCD breaks down (and we rely on phenomenological models)

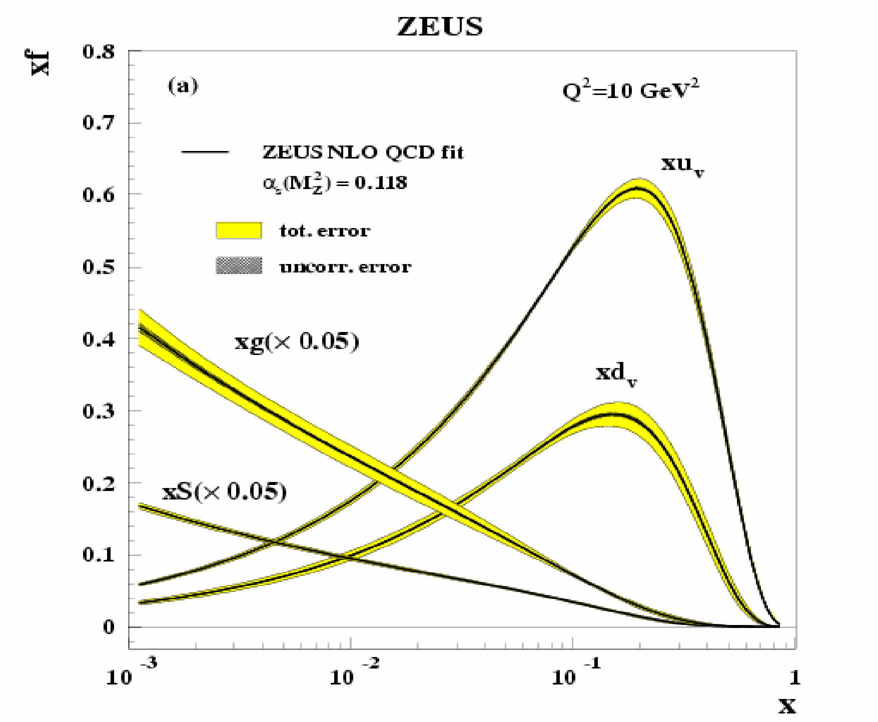
String model for hadronization

QCD Factorization

$$\sigma^{total} = \sum \int dx_1 dx_2 f_q(x_1, Q^2) f_g(x_2, Q^2) \sigma^{parton}$$



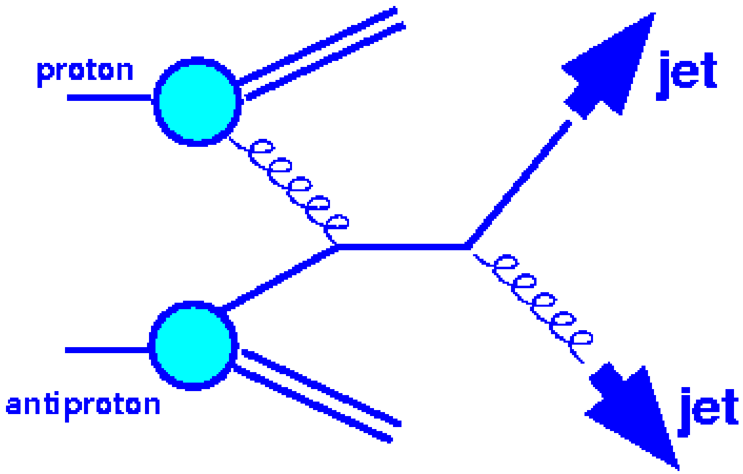
QCD: free quarks and gluons are not allowed…

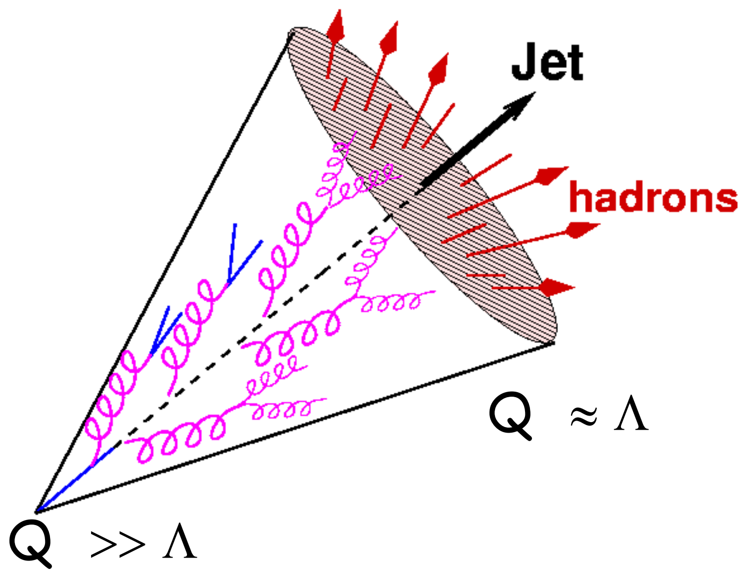


$\hat{\sigma}_{parton}$ Partonic cross section: calculated to a given order in pQCD

$f_q(x_1, Q^2)$ PDFs of parton inside the proton: needs experimental input (universal → can be used to compute different processes)

Jet Physics

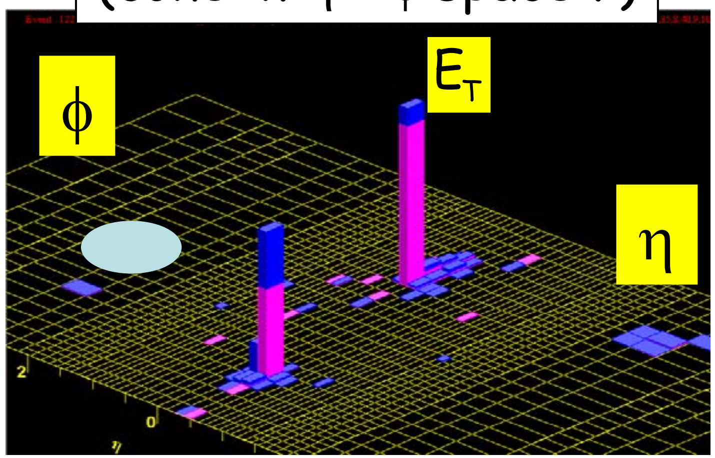


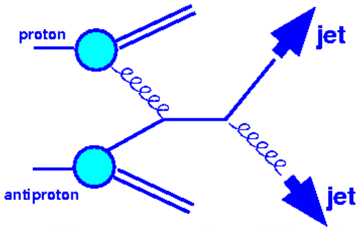


- Final state parton will produce a parton shower (multigluon emissions)
- Parton shower evolves until Q ~1 GeV where hadronization process takes place
- Parton-to-hadron transition depends on the model for gluon shower and hadronization
- To compute cross sections involving quarks and gluons in the final state first one needs to precisely define JETs

$$d\hat{\sigma}_{JET} = d\Phi \, |M|^2 \, F_{JET}$$

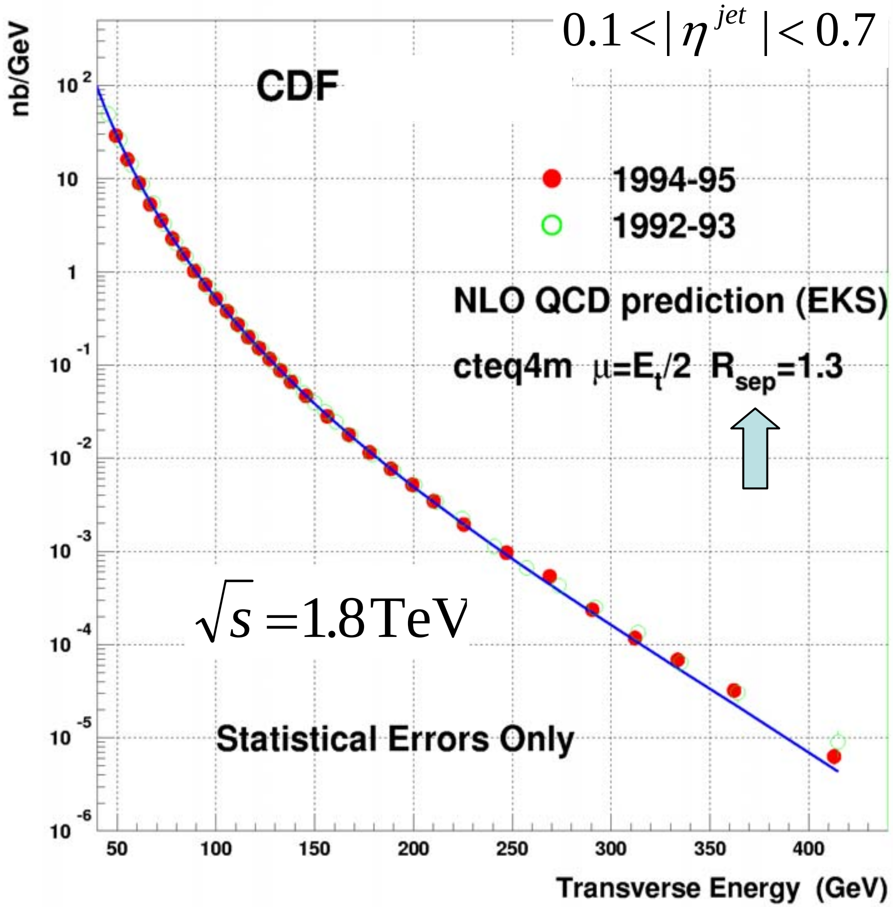
(cone in $\eta - \phi$ space ?)



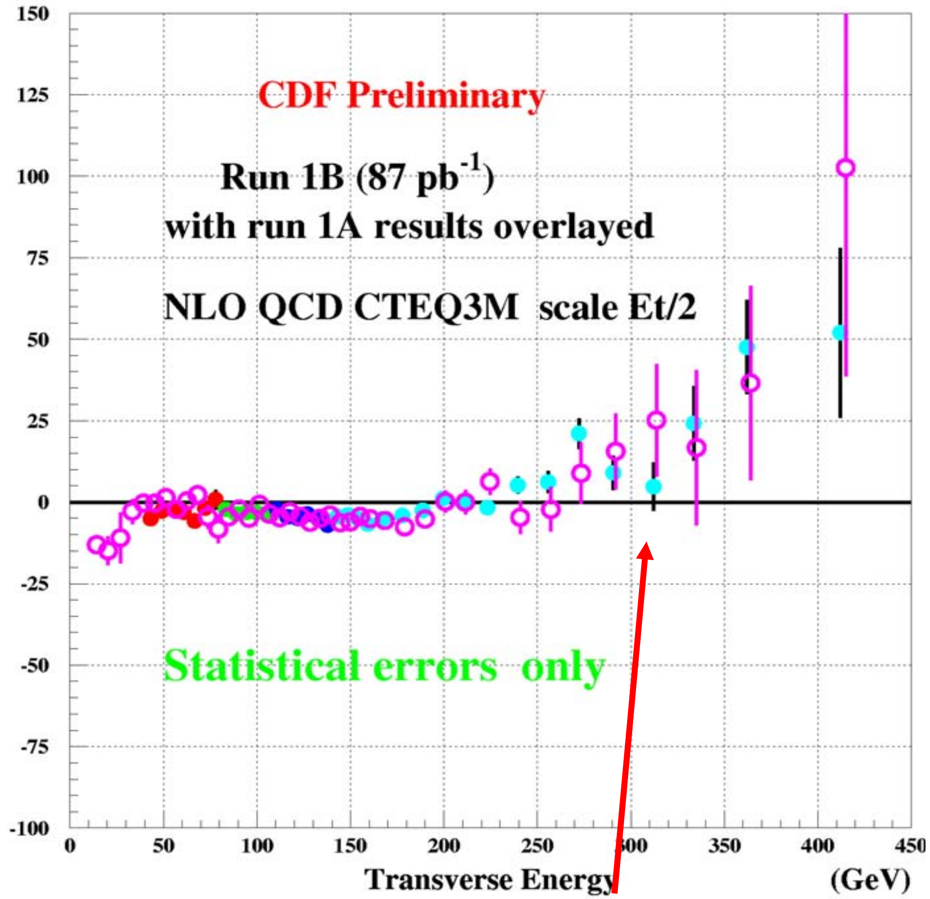


Run I $\frac{d\sigma}{dE_T^{JET}}$ Results

Inclusive Jet cross section

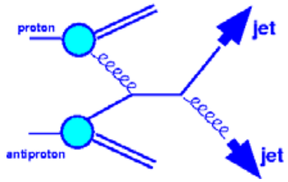


(DATA-THEORY)/THEORY



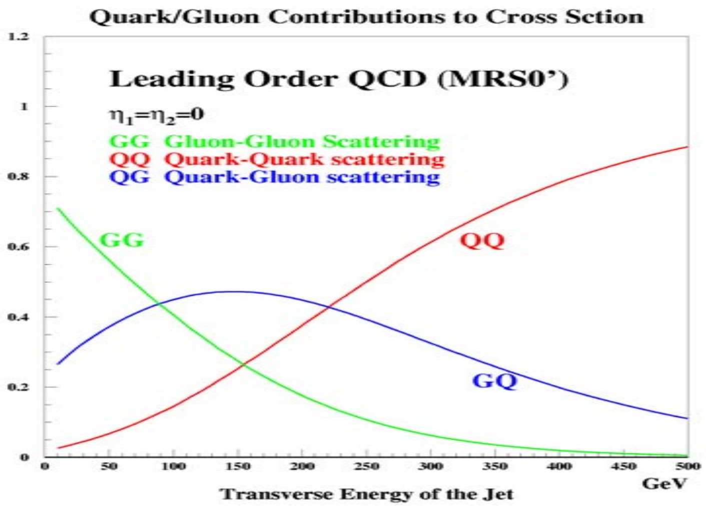
Run I data compared to pQCD NLO

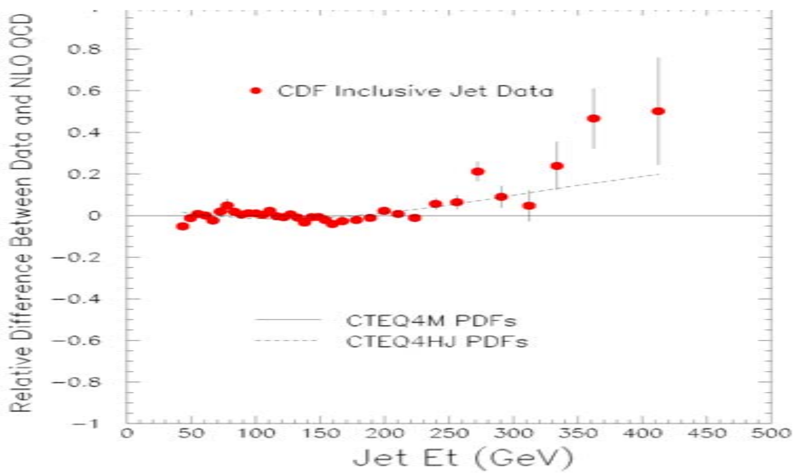
Observed deviation in tail ....
was this a sign of new physics ?

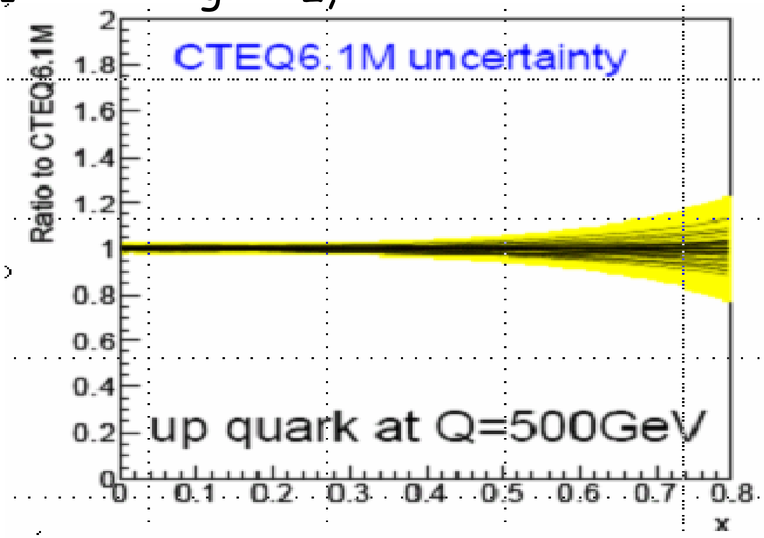


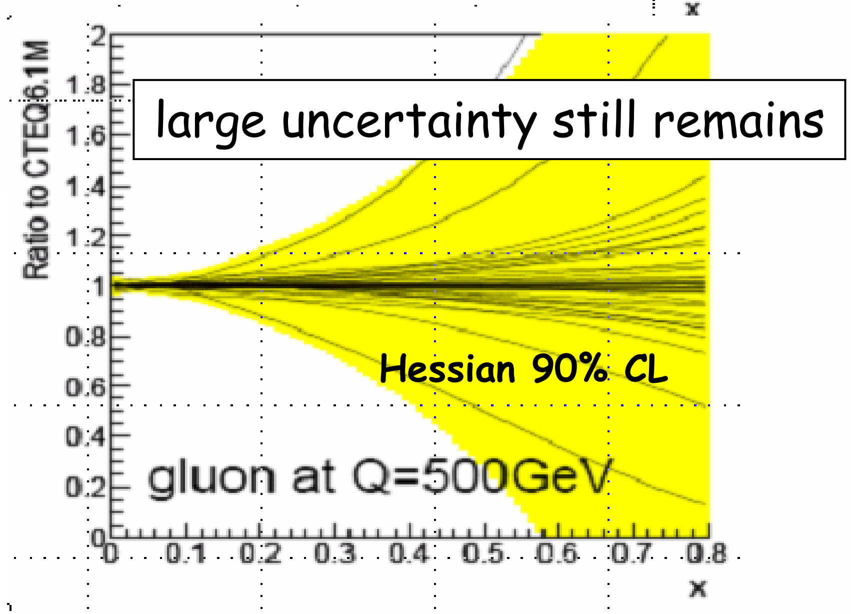
gluon PDFs at high-x

$$\sigma^{total} = \sum \int dx_1 dx_2 f_q(x_1, Q^2) f_g(x_2, Q^2) \sigma^{parton}$$





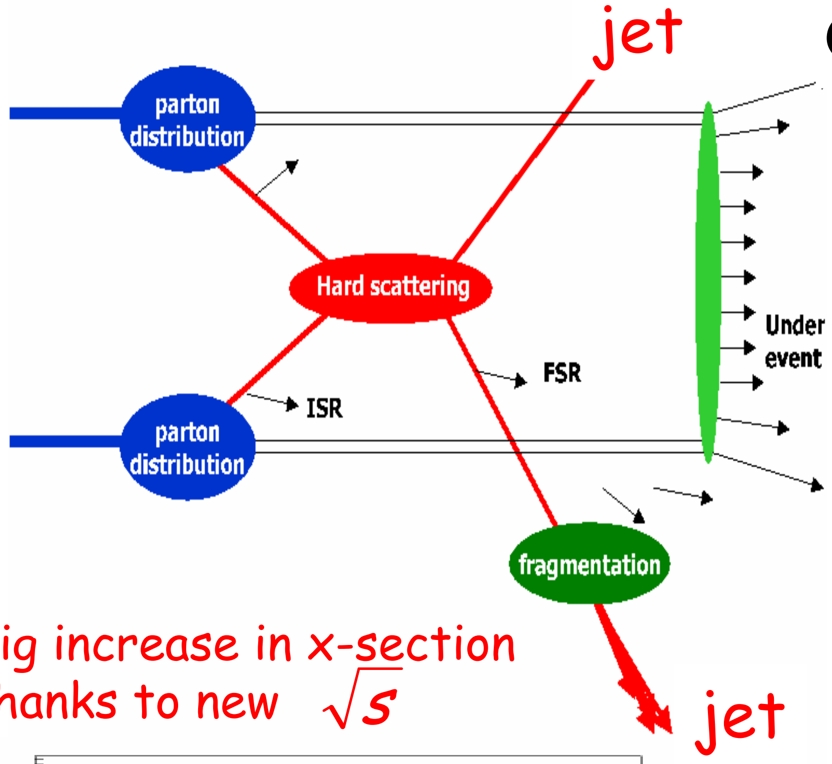


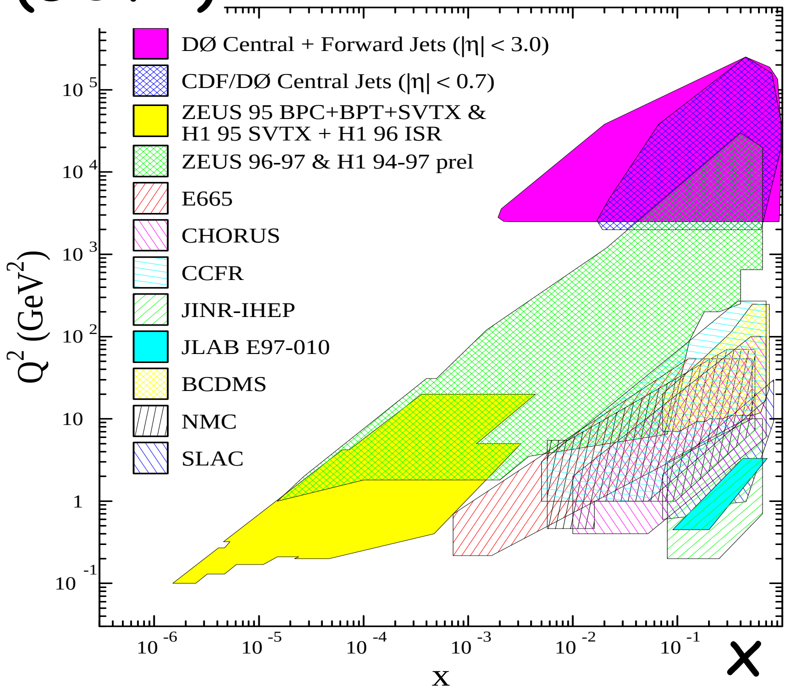


Important GG and GQ contrib. at high-E_T

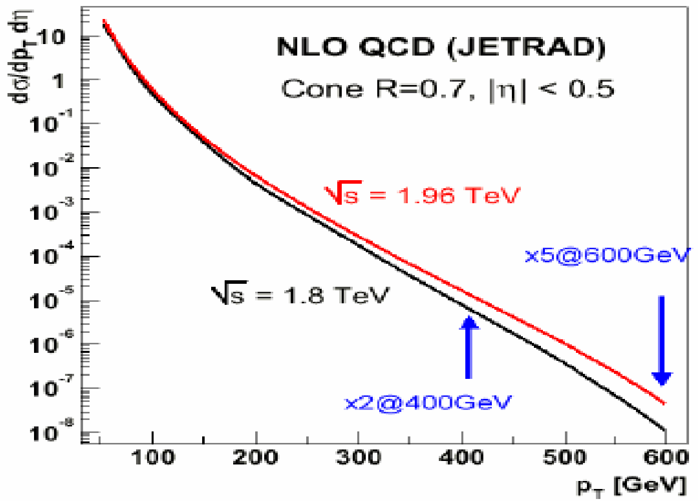
...room for SM explanation....

High Pt Jet Physics at 2 TeV





Big increase in x-section thanks to new $\sqrt{s}$



Huge step forward in Run II

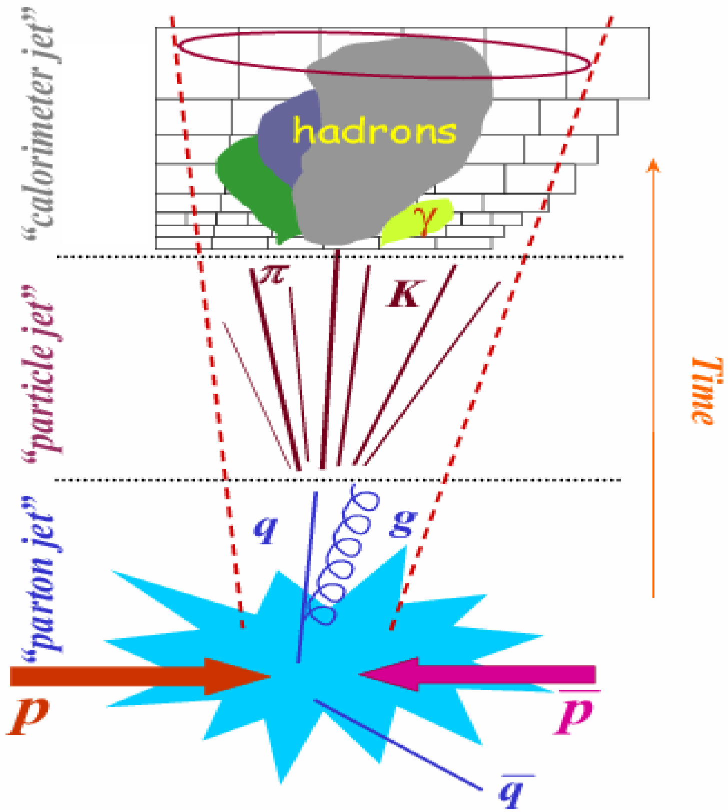
- Pt range increased by 150 GeV/c
- Measurements in wide rapidity region
- Use of K_T and cone jet algorithms
- Inclusion of non-pQCD contributions

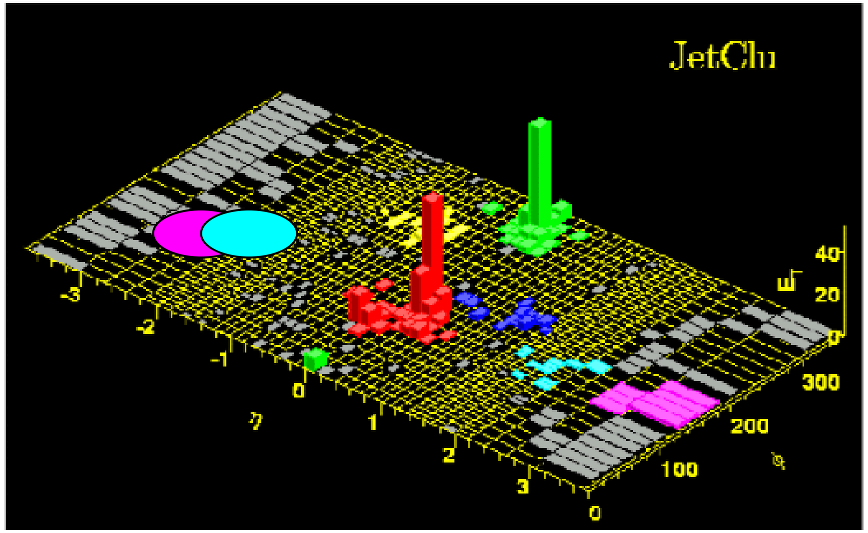
Motivation for the K_T algorithm

- Run I cone-based algorithms is not infrared/collinear safe → Midpoint

- Cone-based jet algorithms include an "experimental" prescription to resolve situations with overlapping cones

- This is emulated in pQCD theoretical calculations by an arbitrary increase of the cone size : R → R' = R * 1.3 ☹





Nature (QCD ?) prefers to separate partons into jets according to their relative transverse momentum

⇩

K_T algorithm preferred by theory

Inclusive K_T Algorithm

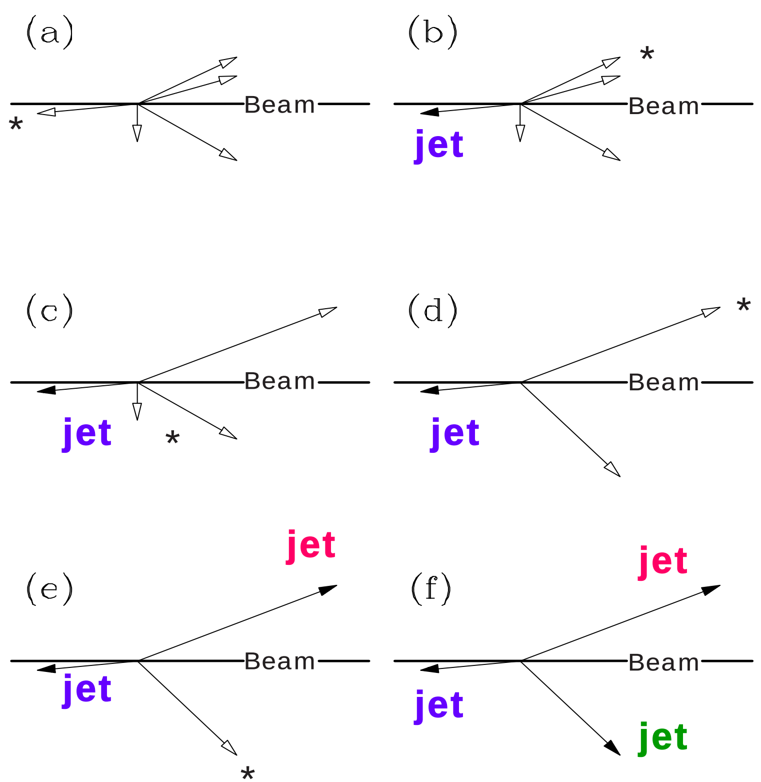
1. Compute for each pair (i,j) and for each particle (i) the quantities:

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$

2. Starting from smallest {d_ij ,d_i}:
3. If it is a d_i then it is called a jet and is removed from the list
4. If it is a d_ij the particles are combined in "proto-jets" (E scheme)
5. Iterate until all particles are in jets

Separation in transverse momentum...
Inspired by pQCD gluon emissions.



☺ No merging/splitting needed!

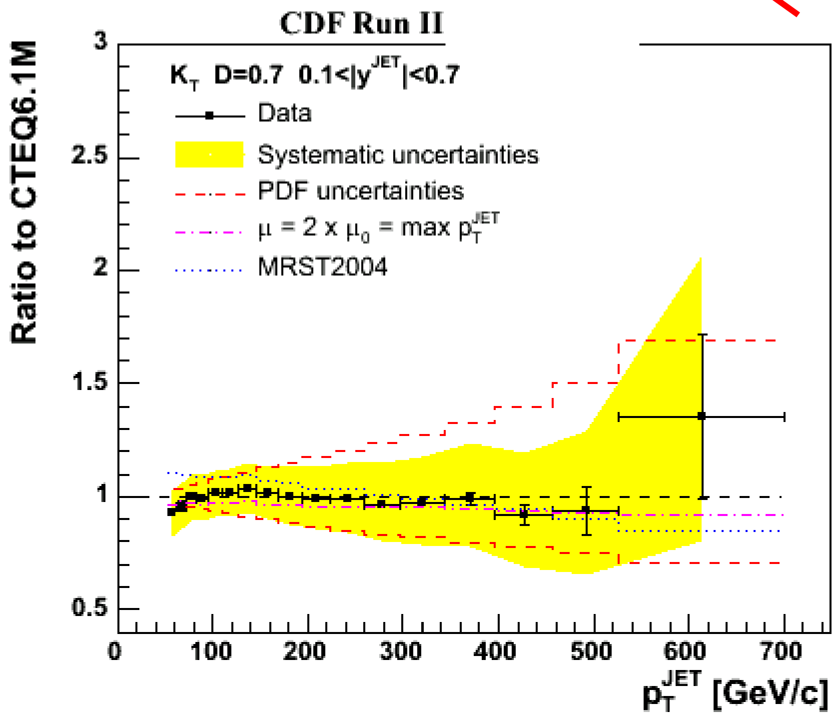
Infrared and Collinear safe to all orders in pQCD

Inclusive Jet Production

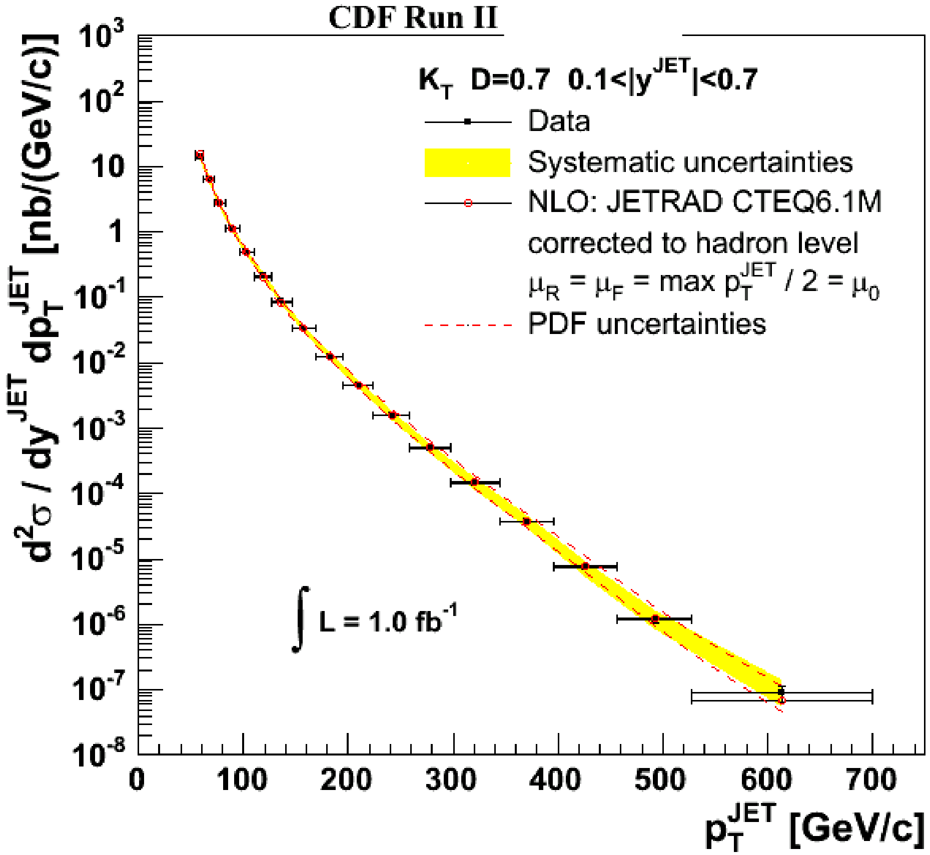
- Inclusive K_T algorithm

$$d_{ij} = \min(P^2{}_{T,i}, P^2{}_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$

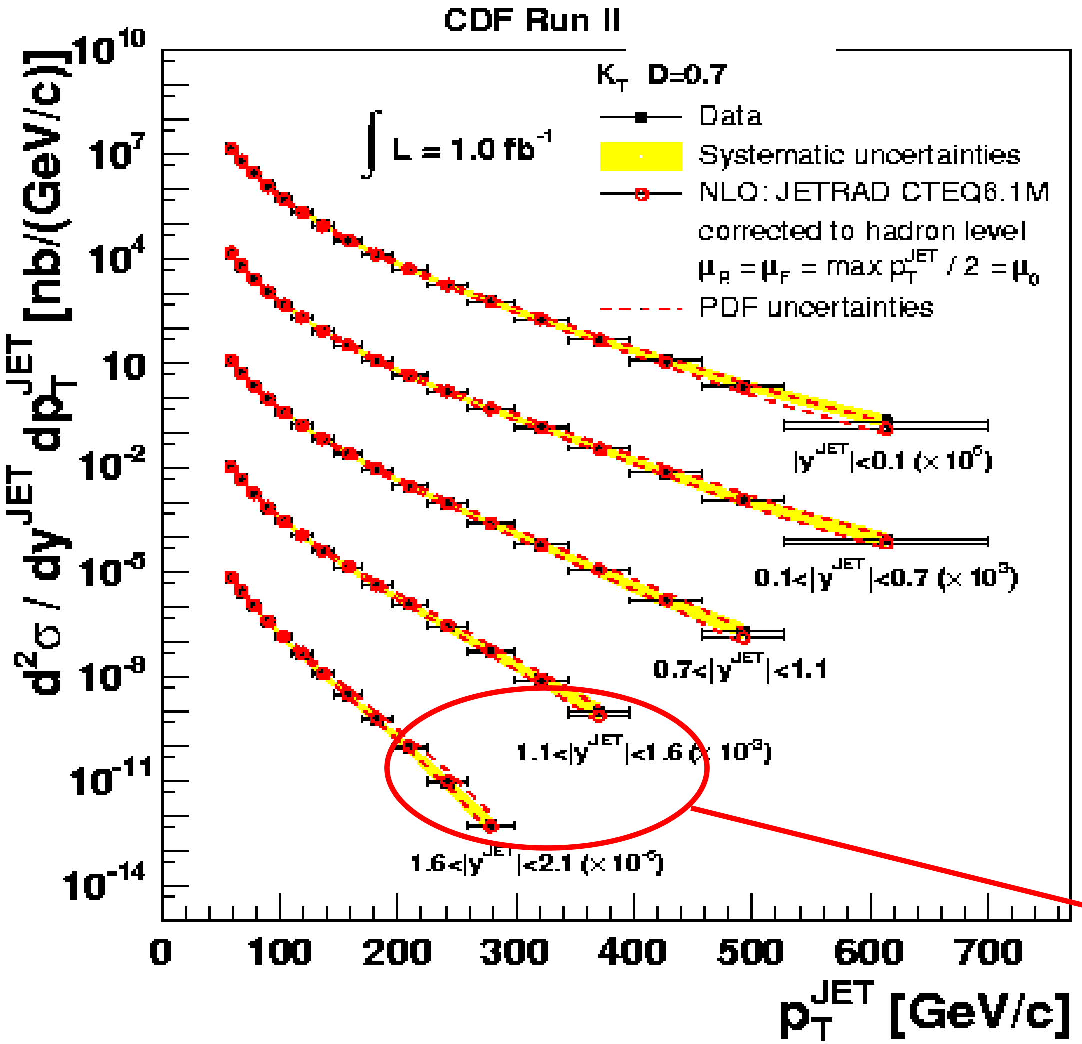


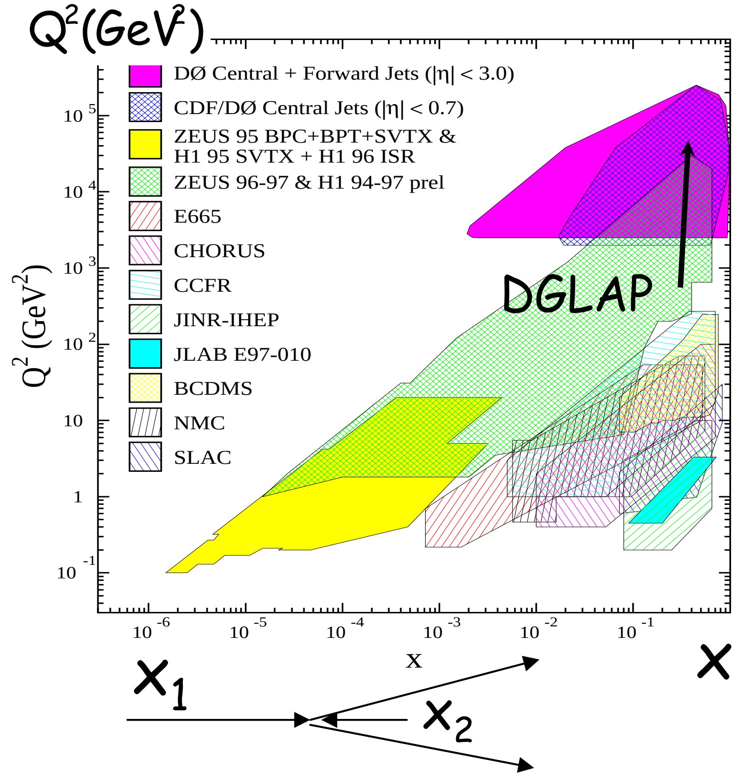
NLO pQCD is corrected for Hadronization & Underlying Event (this is important at low Pt)

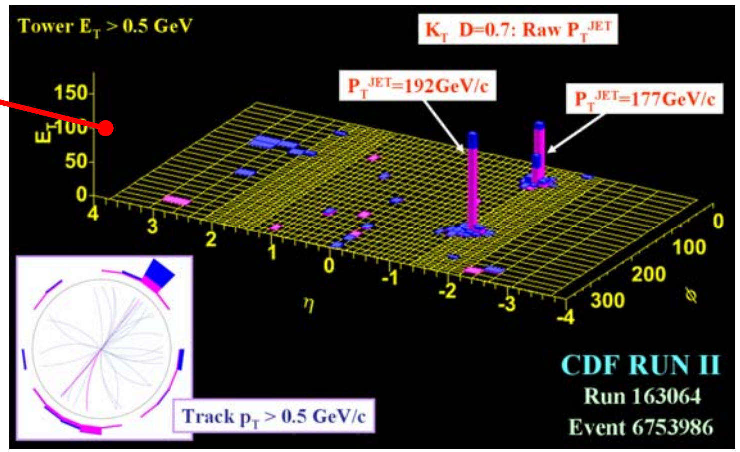


- Good agreement Data vs Theory
  - Data uncertainty -> 2-2.7% e-scale
  - pQCD uncertainty -> PDFs
- K_T robust in hadron collisions
  → relevant for LHC strategies

Measurement in five |Y^jet| ranges

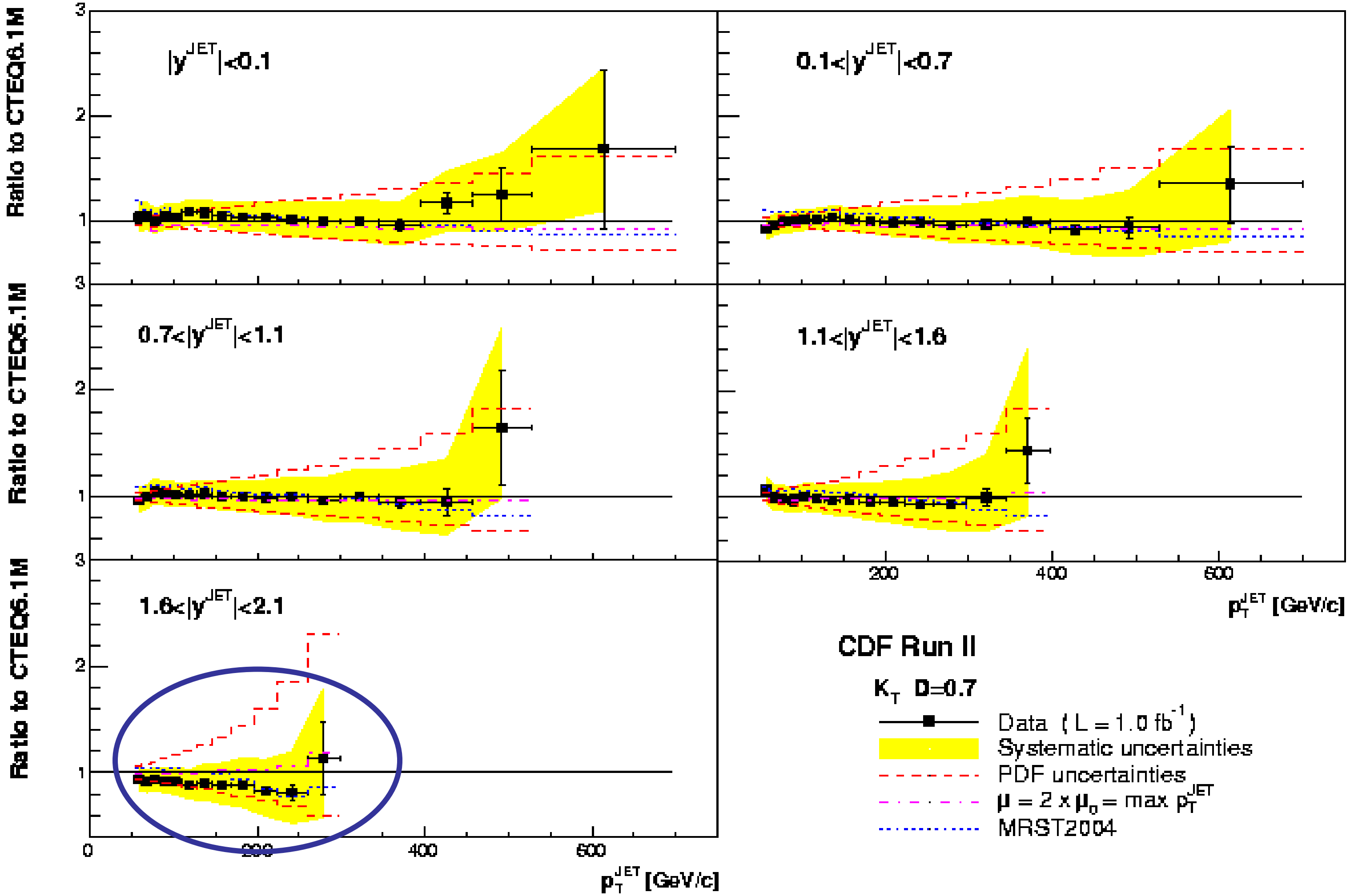






Forward jet measurements further constrain the gluon PDF in a region in P_T where no new physics is expected

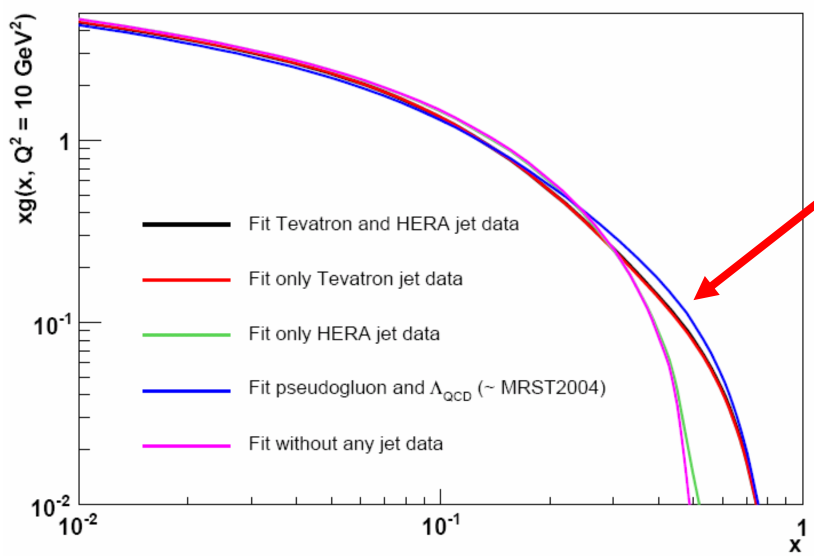
Ratio Data/pQCD NLO



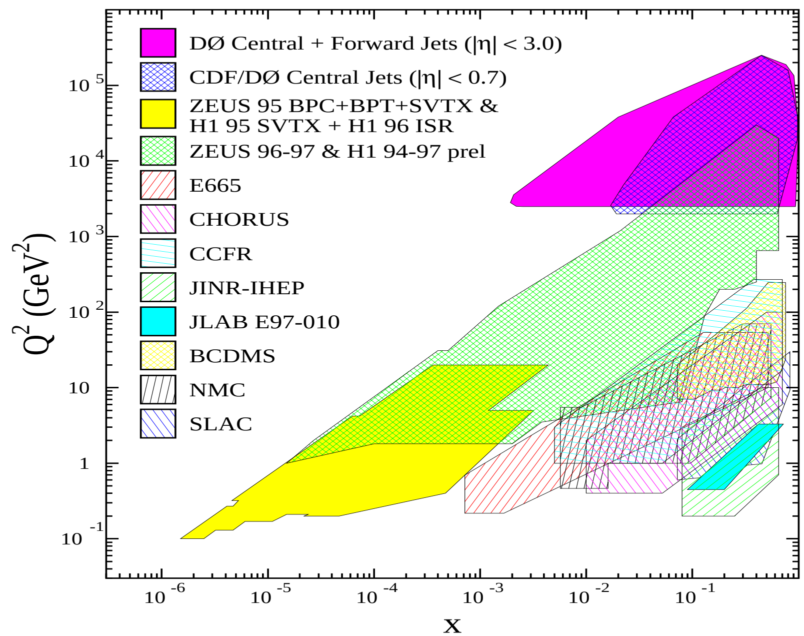
Data uncertainty smaller than that on pQCD NLO
CDF contribution to a better knowledge of gluon PDF

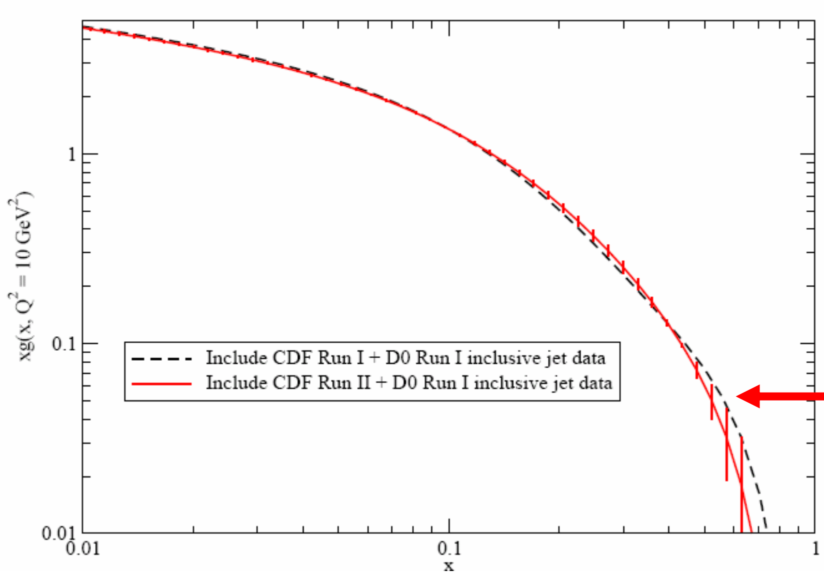
(March 2007)

New Gluon (MRST/MSTW)



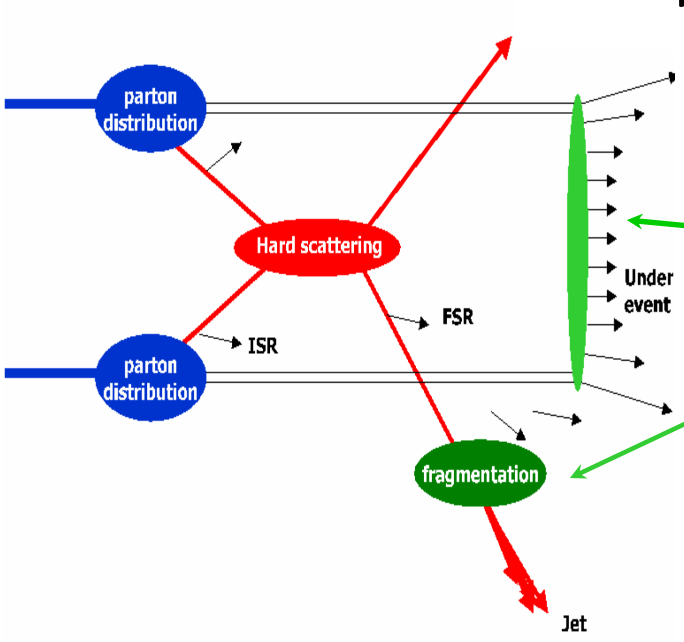
Tevatron data is the only constrain for gluon PDF for x>0.3



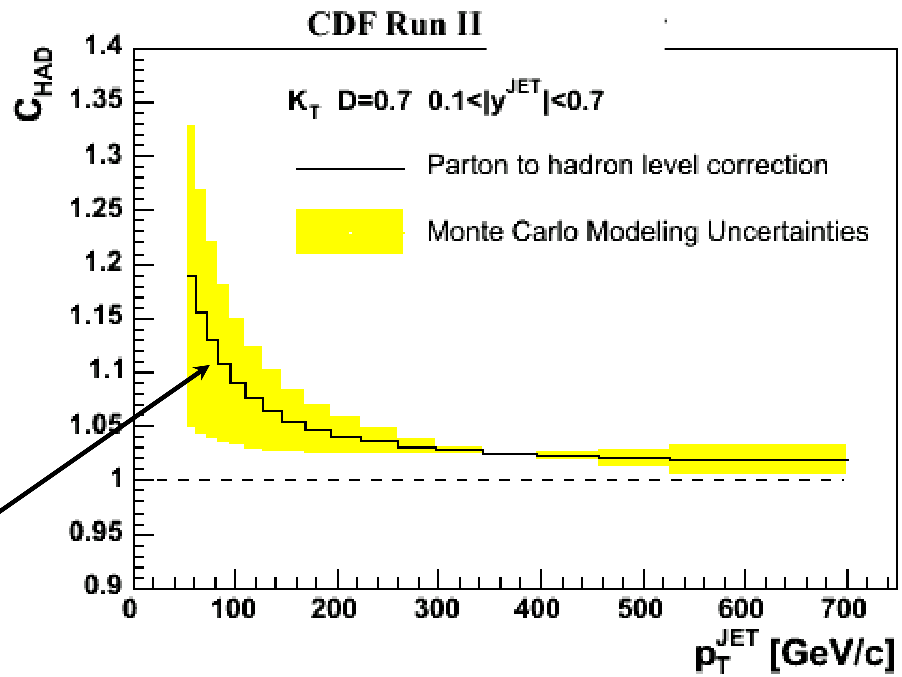


New data prefer less gluons at high-x (significant change)

Non-pQCD Contributions



- Non-pQCD contributions
- Underlying Event
(remnant-remnant interactions)
- Fragmentation into hadrons



Underlying Event and Fragmentation contributions must be considered before comparing to NLO QCD predictions
(only way to perform a fair comparison)

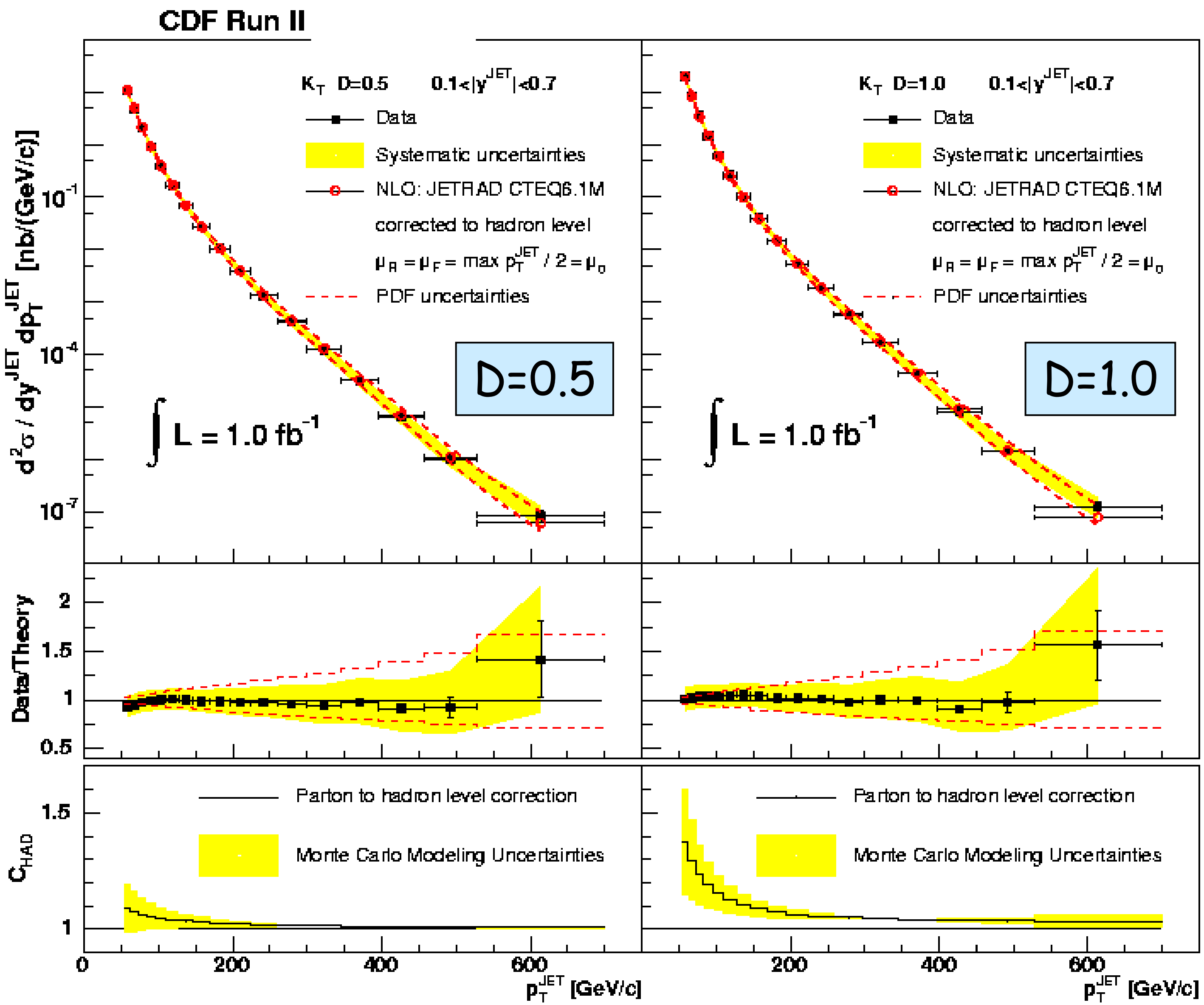
Precise measurements at low Pt require good modeling of the non-pQCD terms

Dedicated measurements are needed to validate the Monte Carlo modeling

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j})\frac{\Delta R^2}{D^2}$$

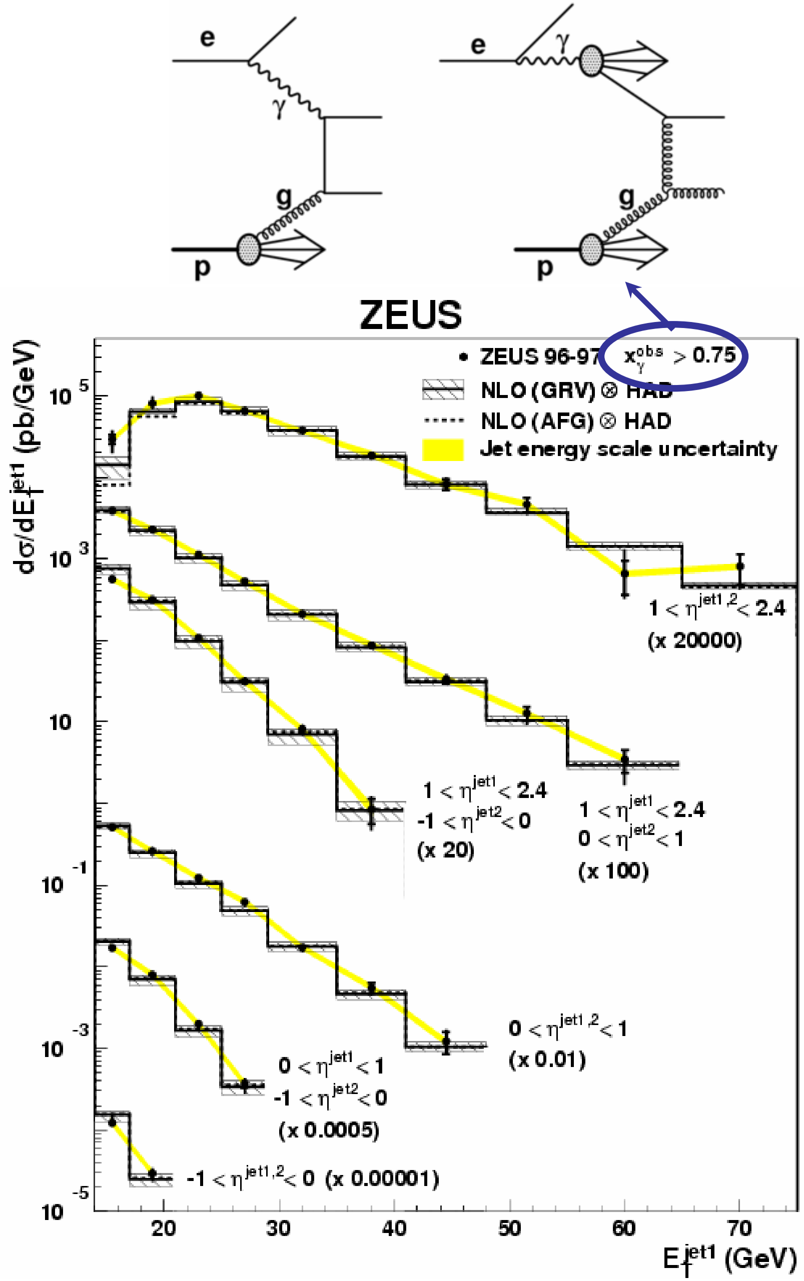
K_T Jets vs D

1 fb^{-1}

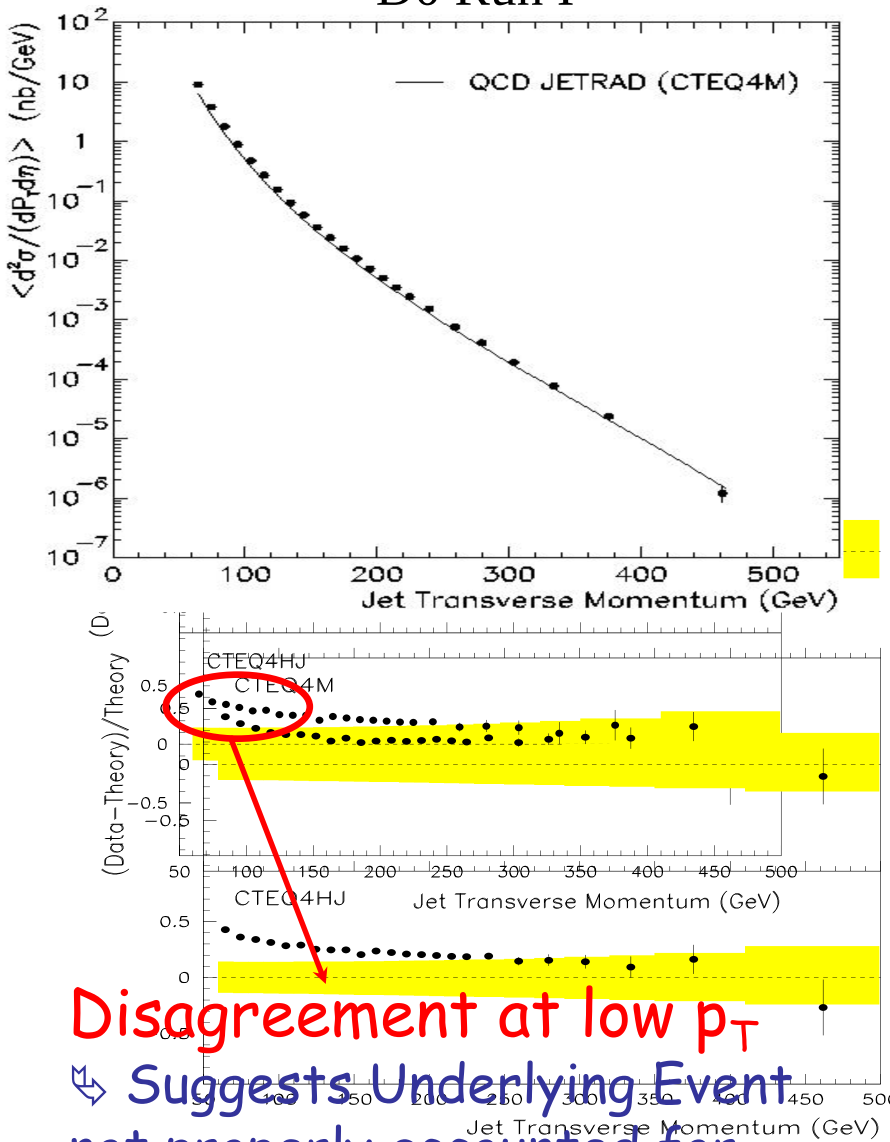


As D increases the required non-perturbative corrections increase at low P_T

Results from ZEUS / D0 Run I



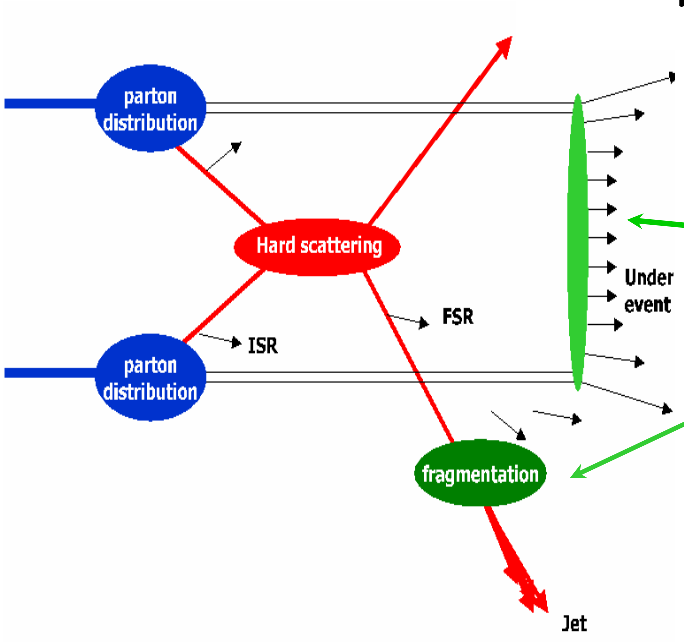
D0 Run I



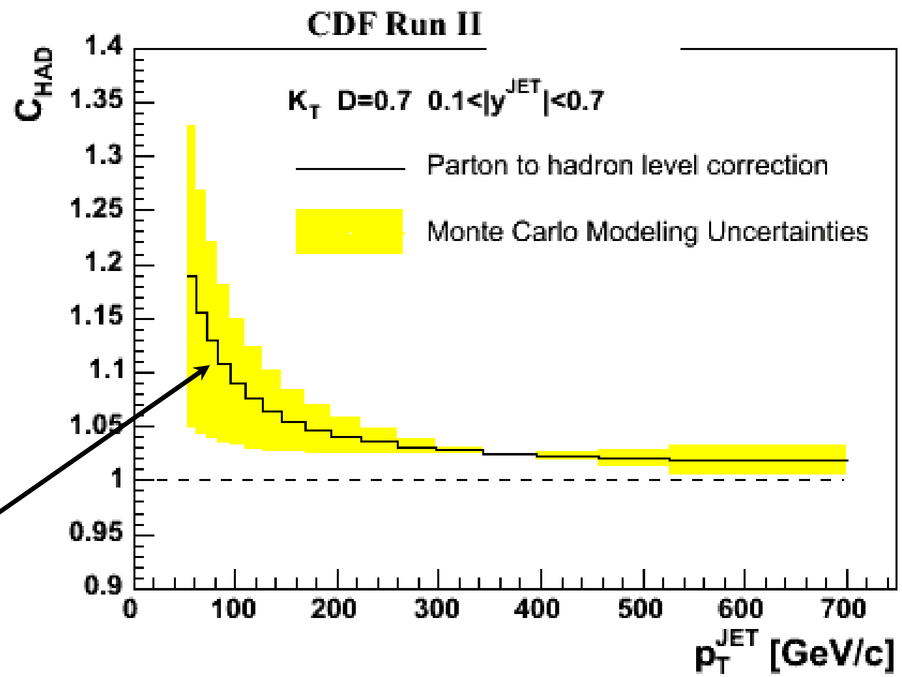
Disagreement at low p_T

↳ Suggests Underlying Event not properly accounted for

Non-pQCD Contributions



- Non-pQCD contributions
- Underlying Event (remnant-remnant interactions)
- Fragmentation into hadrons



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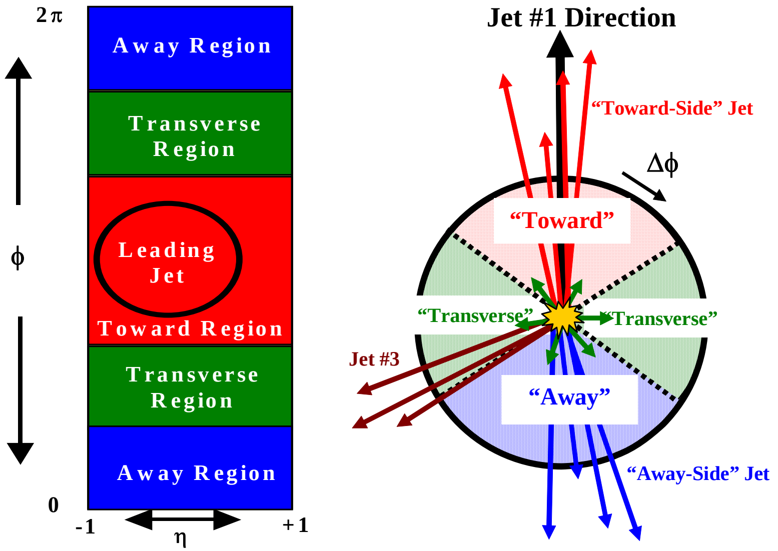
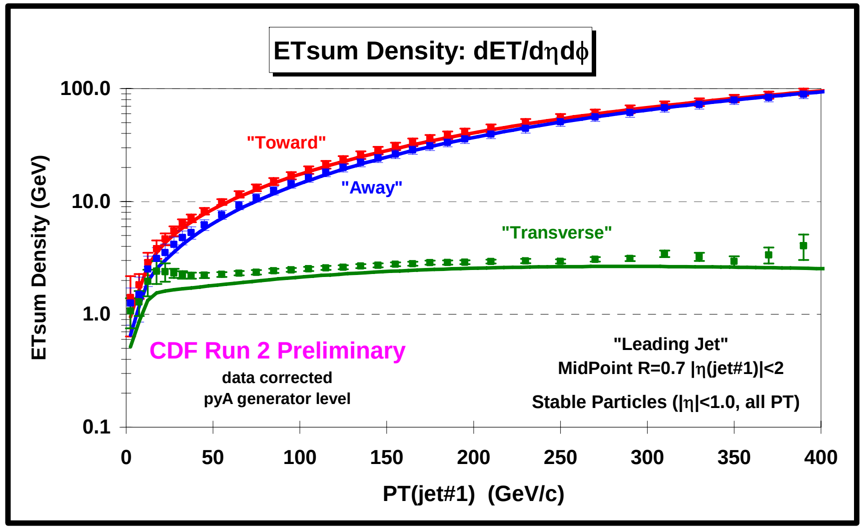
(only way to perform a fair comparison)

Precise measurements at low Pt require good modeling of the non-pQCD terms

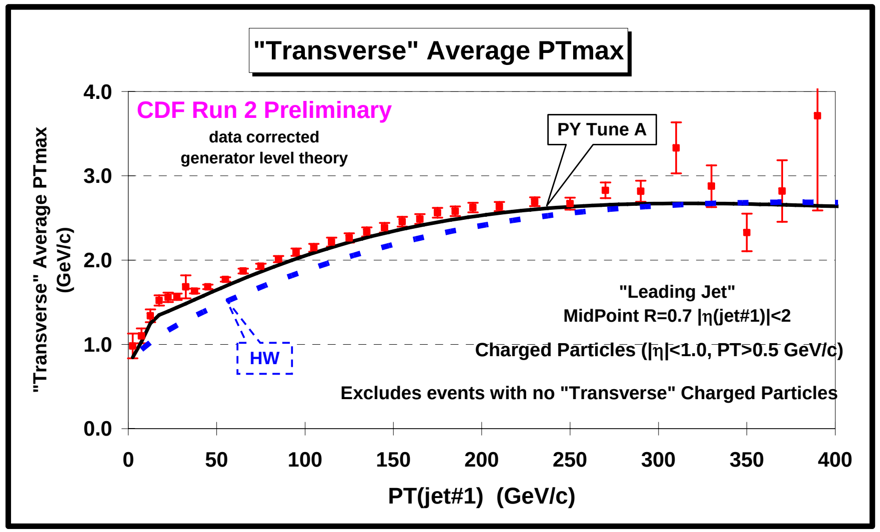
Dedicated measurements are needed to validate the Monte Carlo modeling

Underlying Event Studies





$$p_T^{track} > 0.5\,\text{GeV}, \quad |\eta^{track}| < 1$$

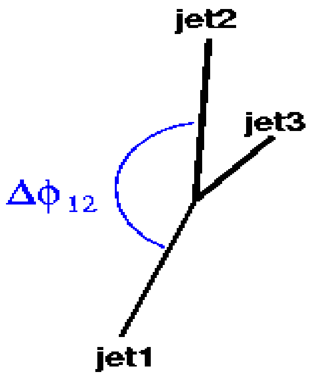


transverse region sensitive to soft underlying event activity

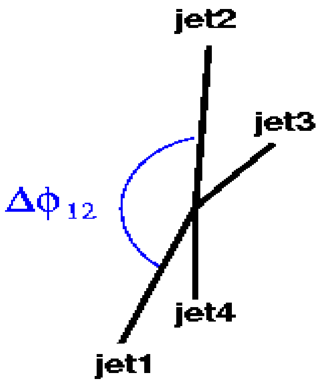
Good description of the underlying event by PYTHIA after tuning the amount of initial state radiation, MPI and selecting CTEQ5L PDFs (known as PYTHIA Tune A)

Studies on $\Delta\phi$ between jets

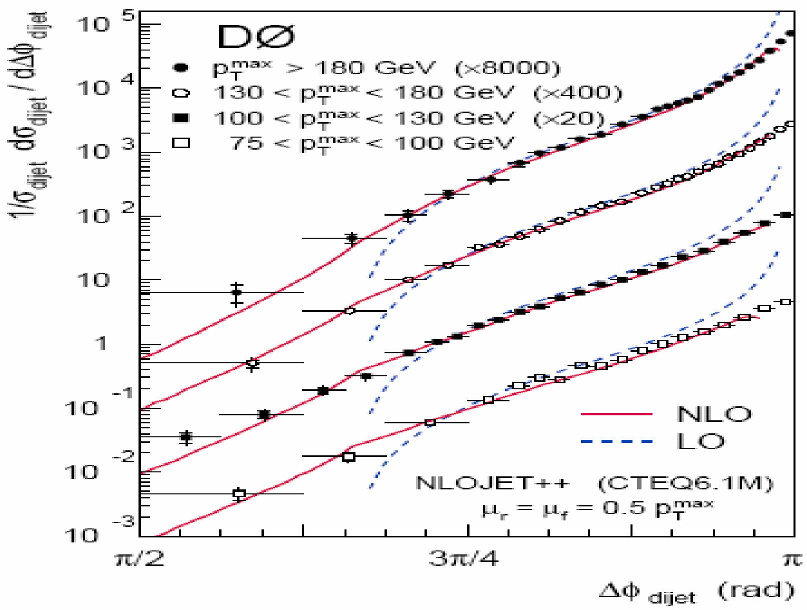
Using the Midpoint Jet Algorithm

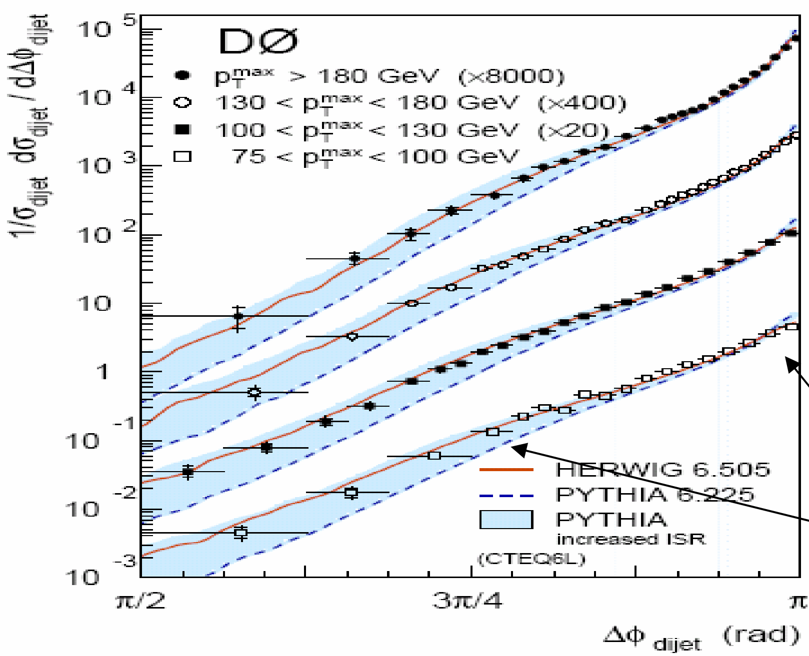


LO in $\Delta\phi$



NLO in $\Delta\phi$





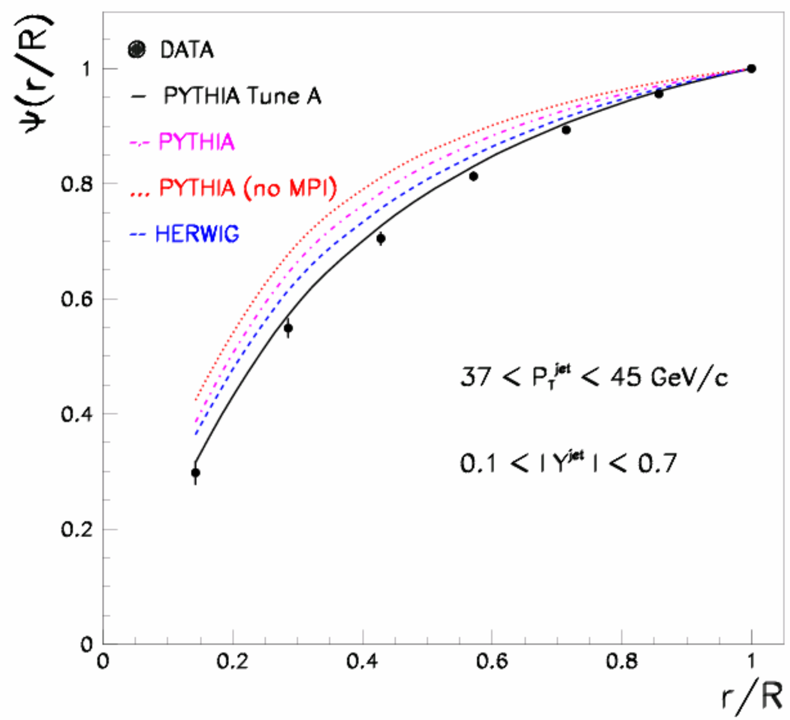
LO dominated by collinear topologies

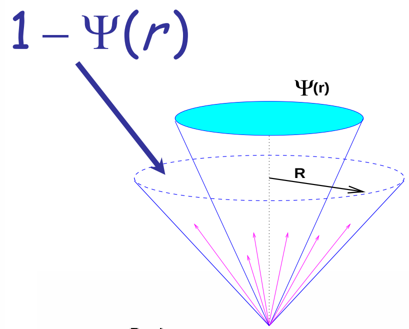
NLO closer to the data

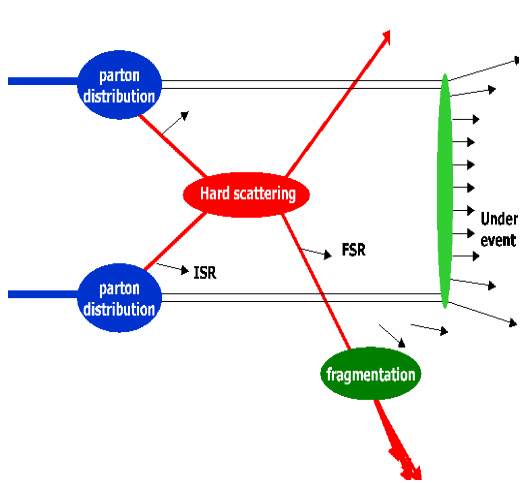
(region around π requires soft gluons…)

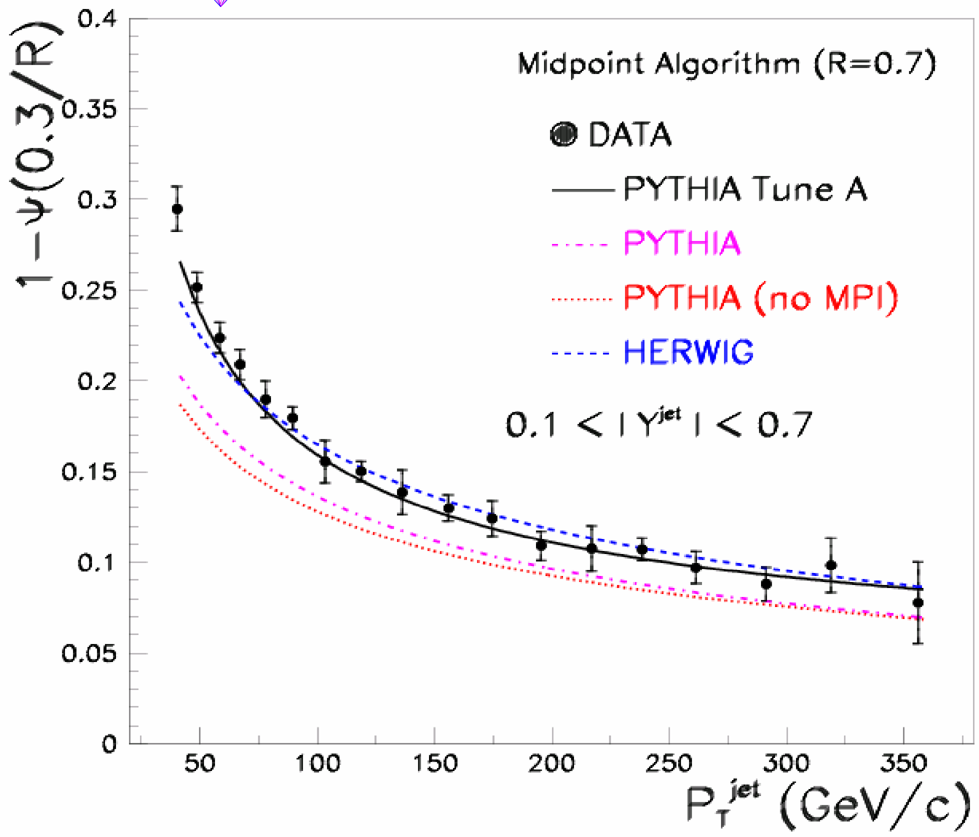
Sensitive to implementation of ISR of soft gluons in parton shower MCs

Jet shapes







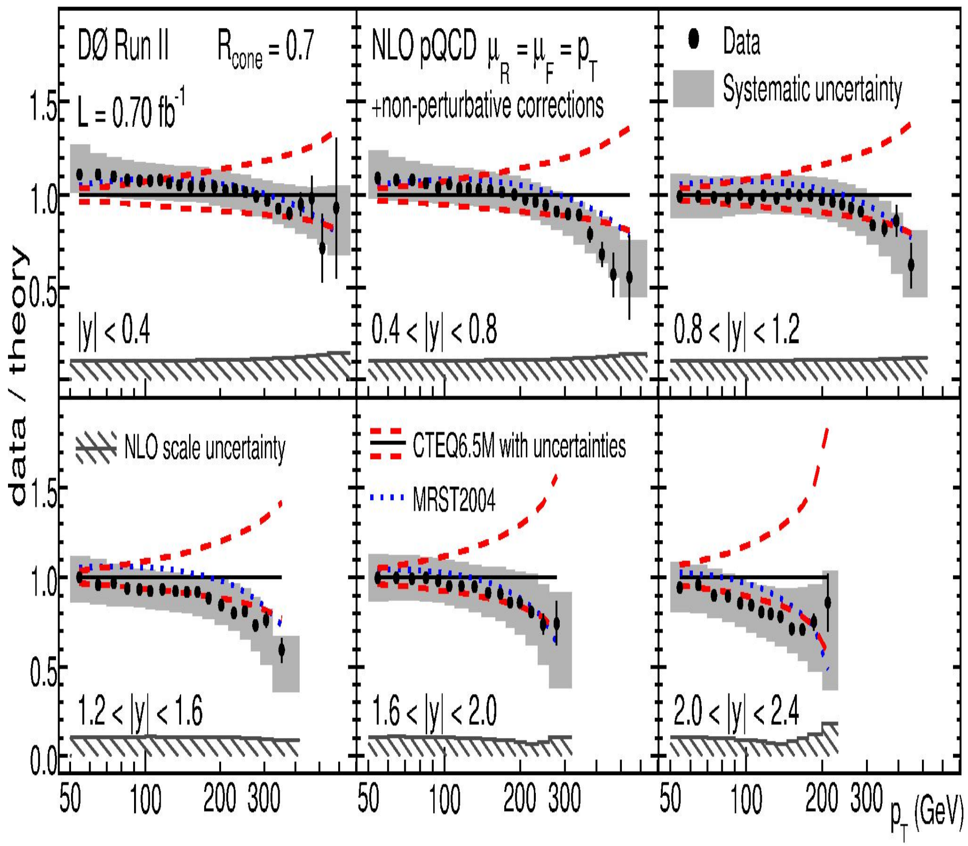


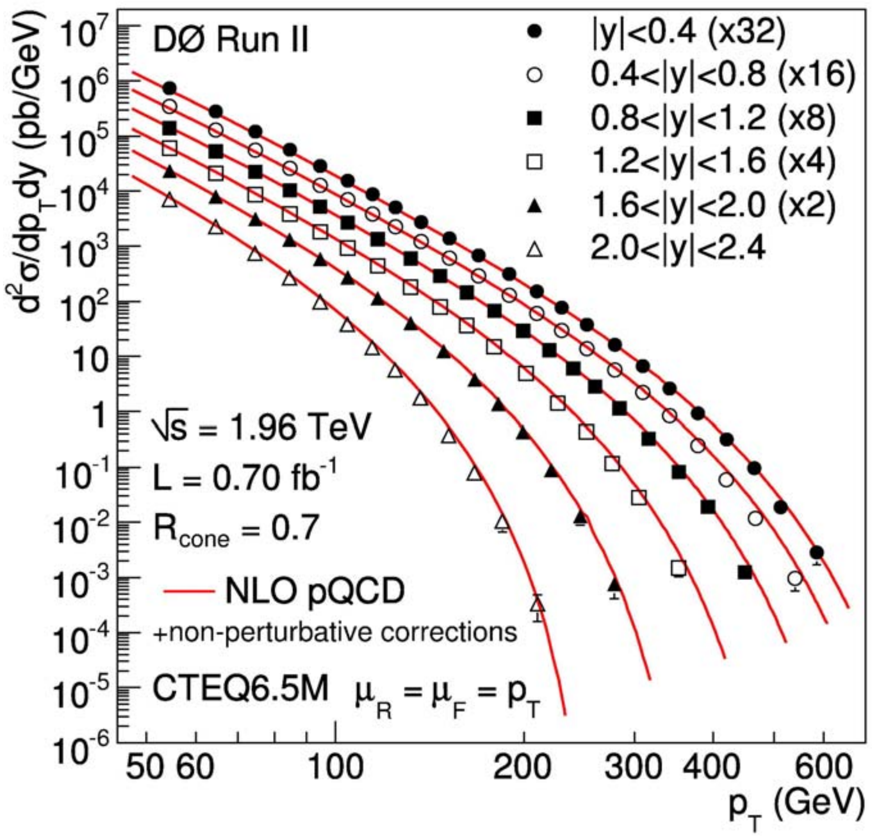
- PYTHIA Tune A describes the data (enhanced ISR + MPI tuning)
- PYTHIA default too narrow
- MPI are important at low Pt
- HERWIG too narrow at low Pt

We know how to model the UE at 2 TeV for QCD jet processes

Latest D0 Jet Results

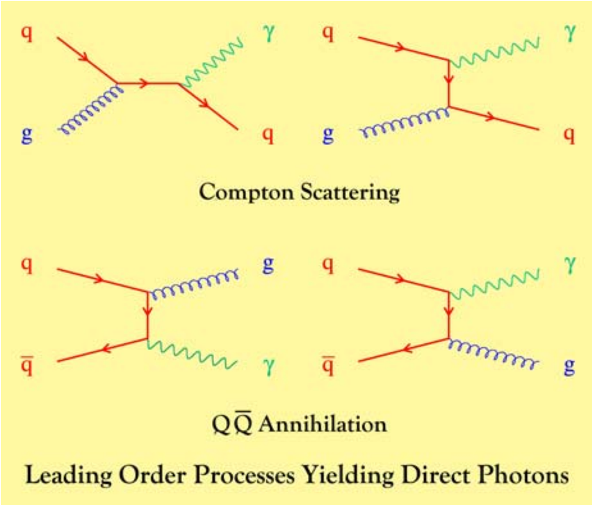
Using cone-based Midpoint Algorithm (R=0.7)

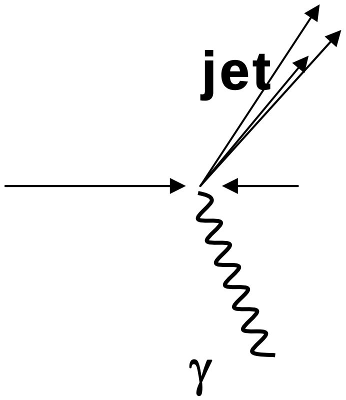


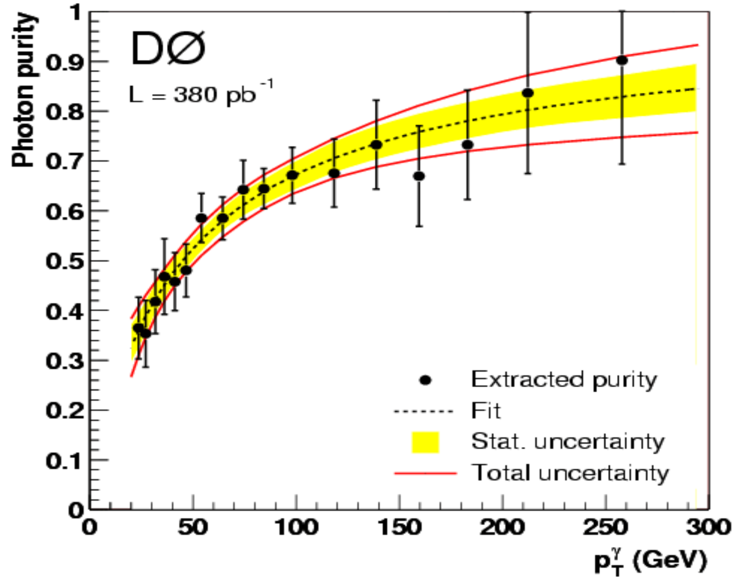


Similar conclusions using the midpoint algorithm ….and reduced systematic uncertainties on the absolute jet energy scale (1.2% - 2%)

Direct Photon Production



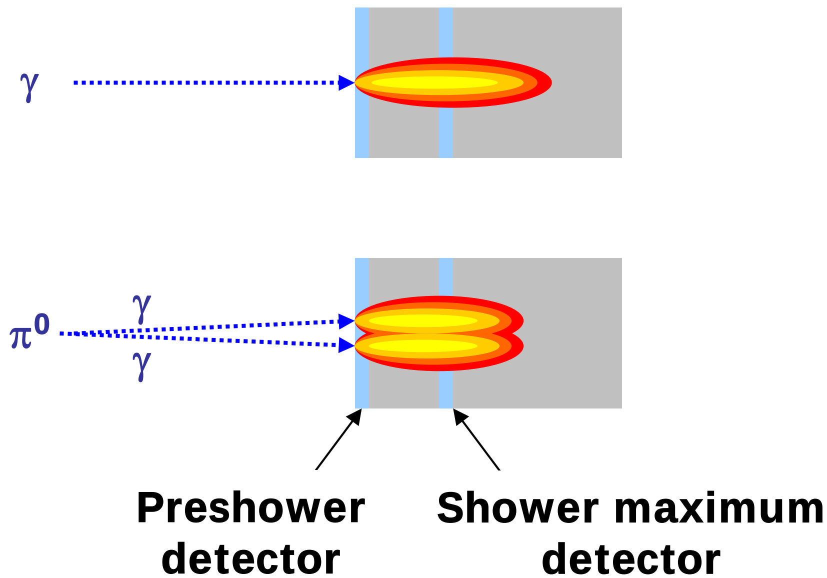




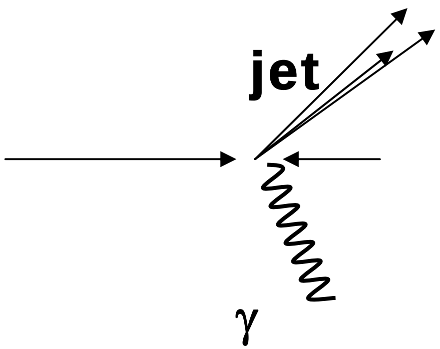
Using prompt photons one can precisely study QCD dynamics:

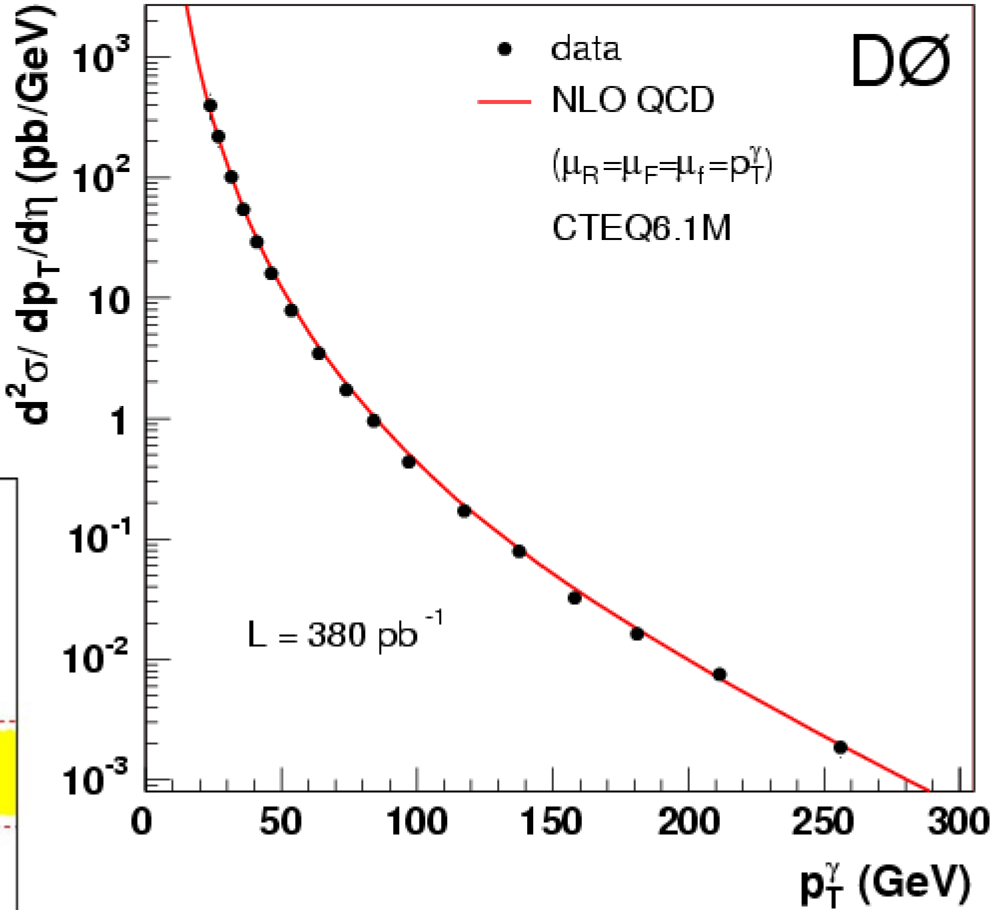
- Well known coupling to quarks
- Give access to lower Pt
- Clean: no need to define "jets"
- constrain of gluon PDF

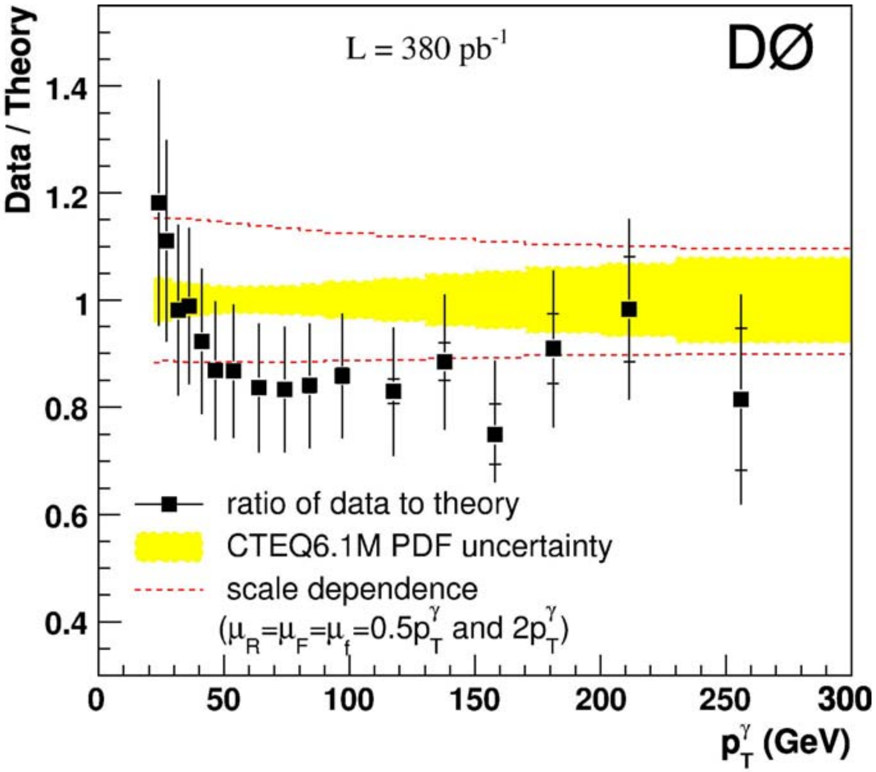
Experimentally difficult because of large background from π^0 decays



Pt Distribution of Photons



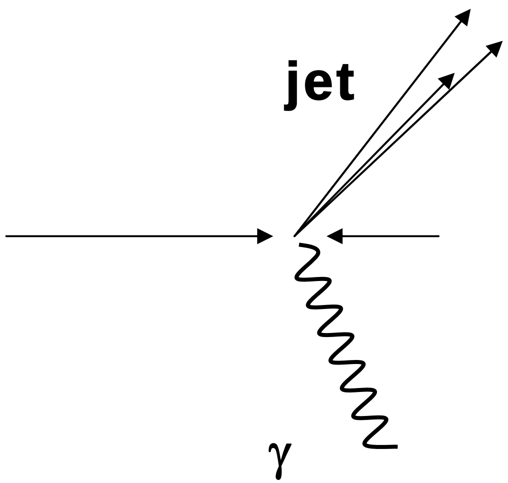


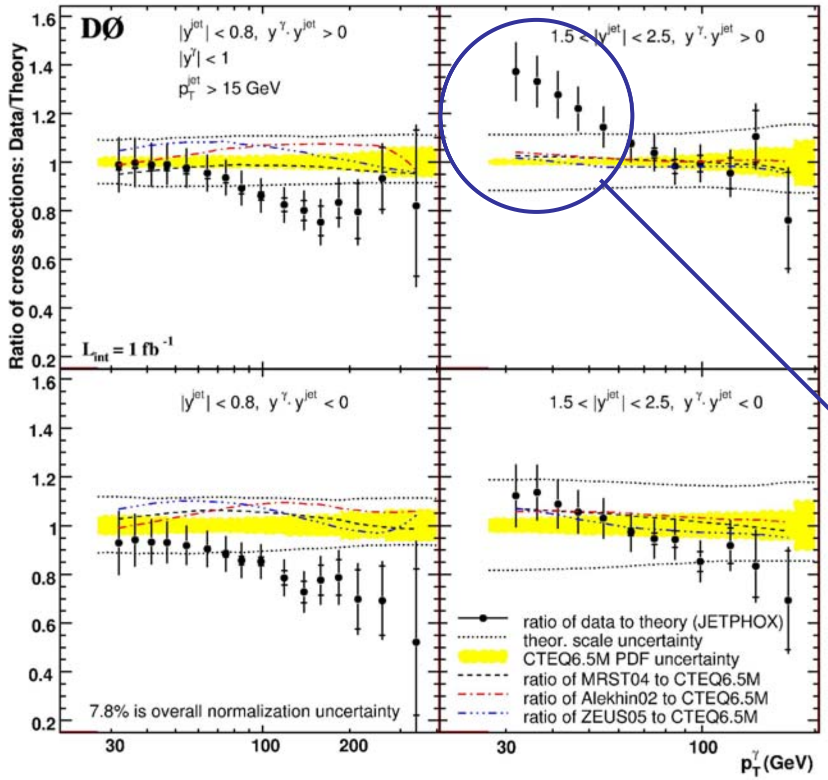


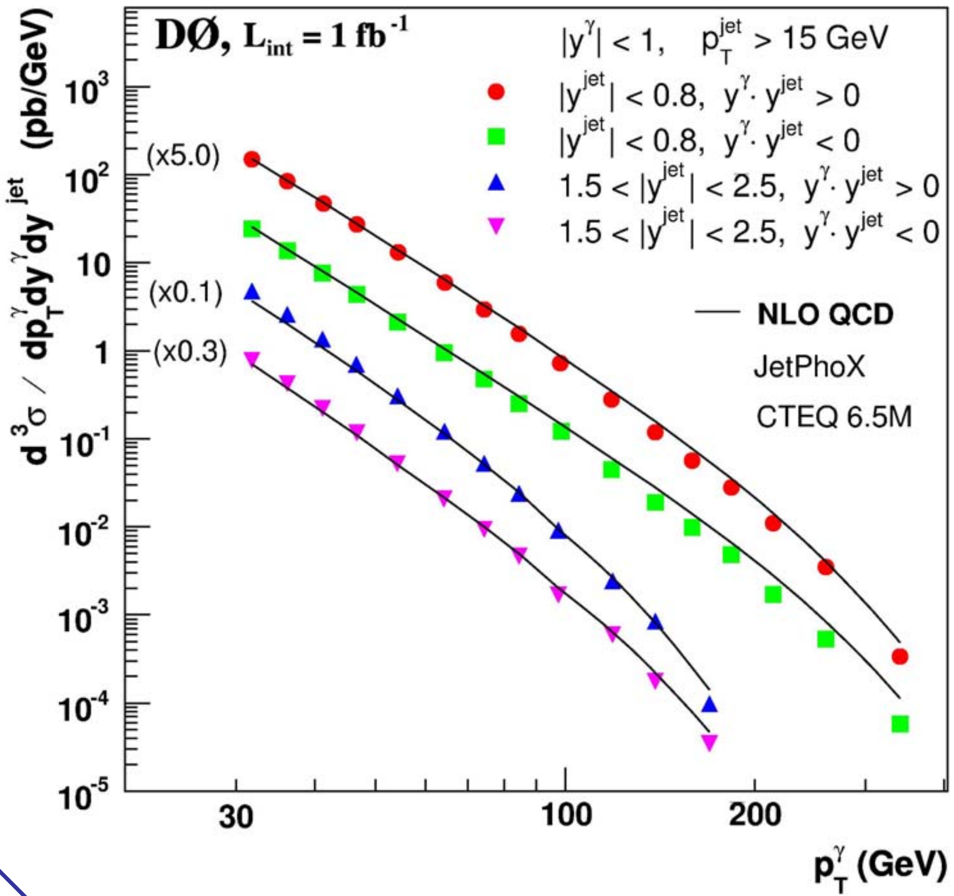
Good agreement with pQCD NLO
(good understanding of photon e-scale)

Very promising at the fb-1 level
to constrain gluon PDFs at high x

γ+jets results



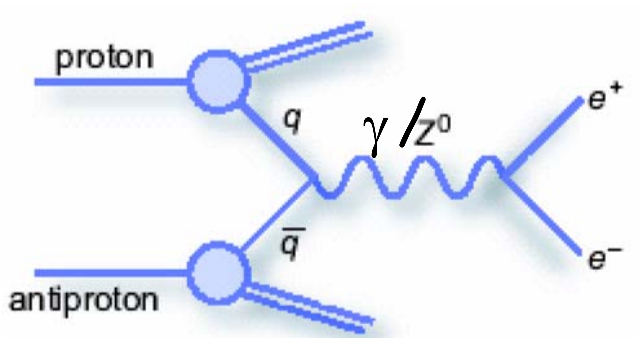


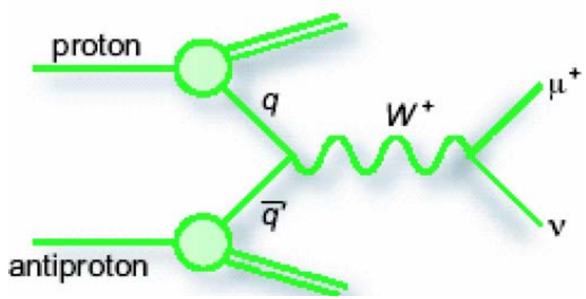


NLO pQCD prediction not really able to follow the data in some regions of the photon-jet phase space

Results are input to future theoretical work on NLO calculations

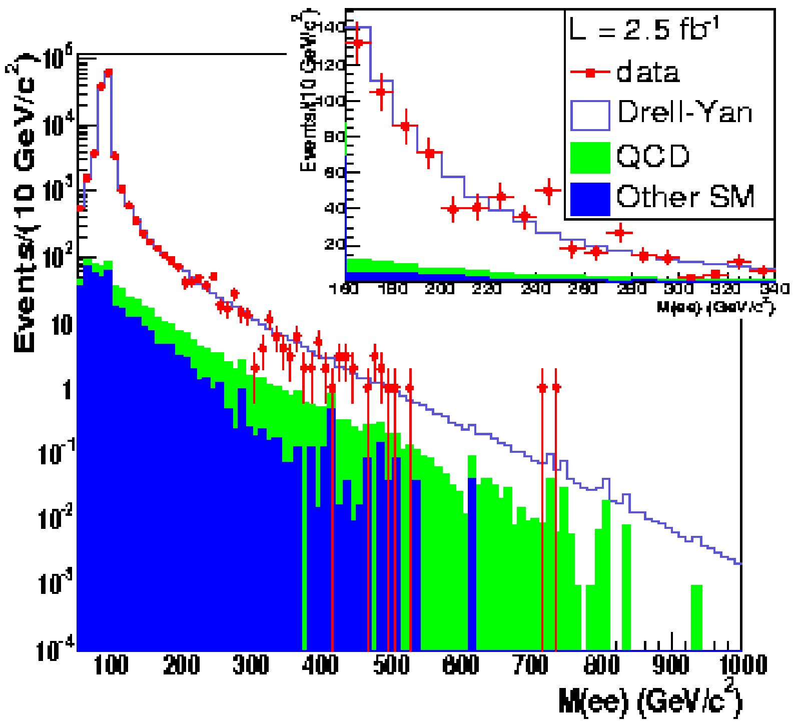
Drell-Yan Processes

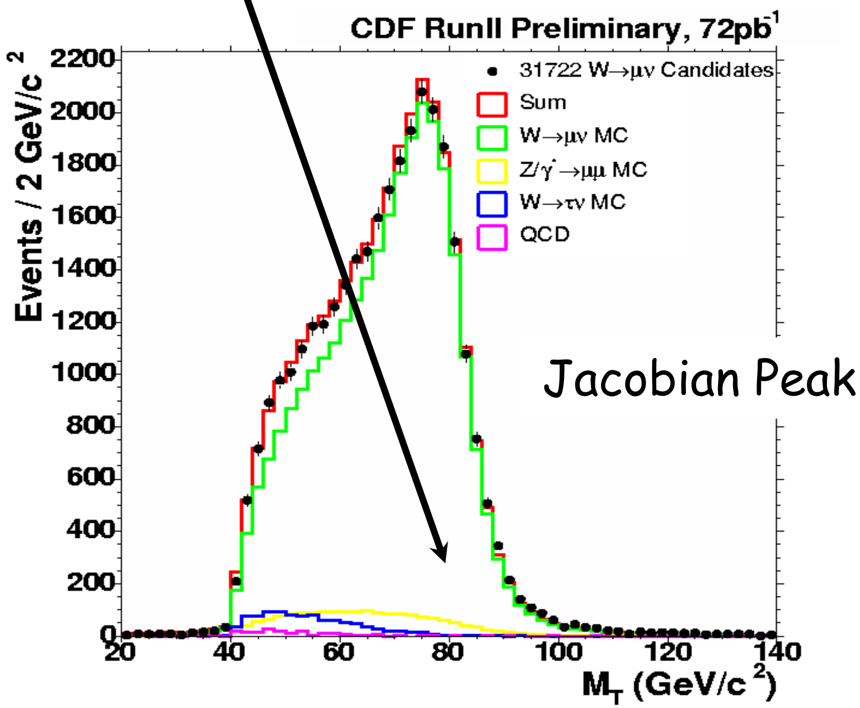




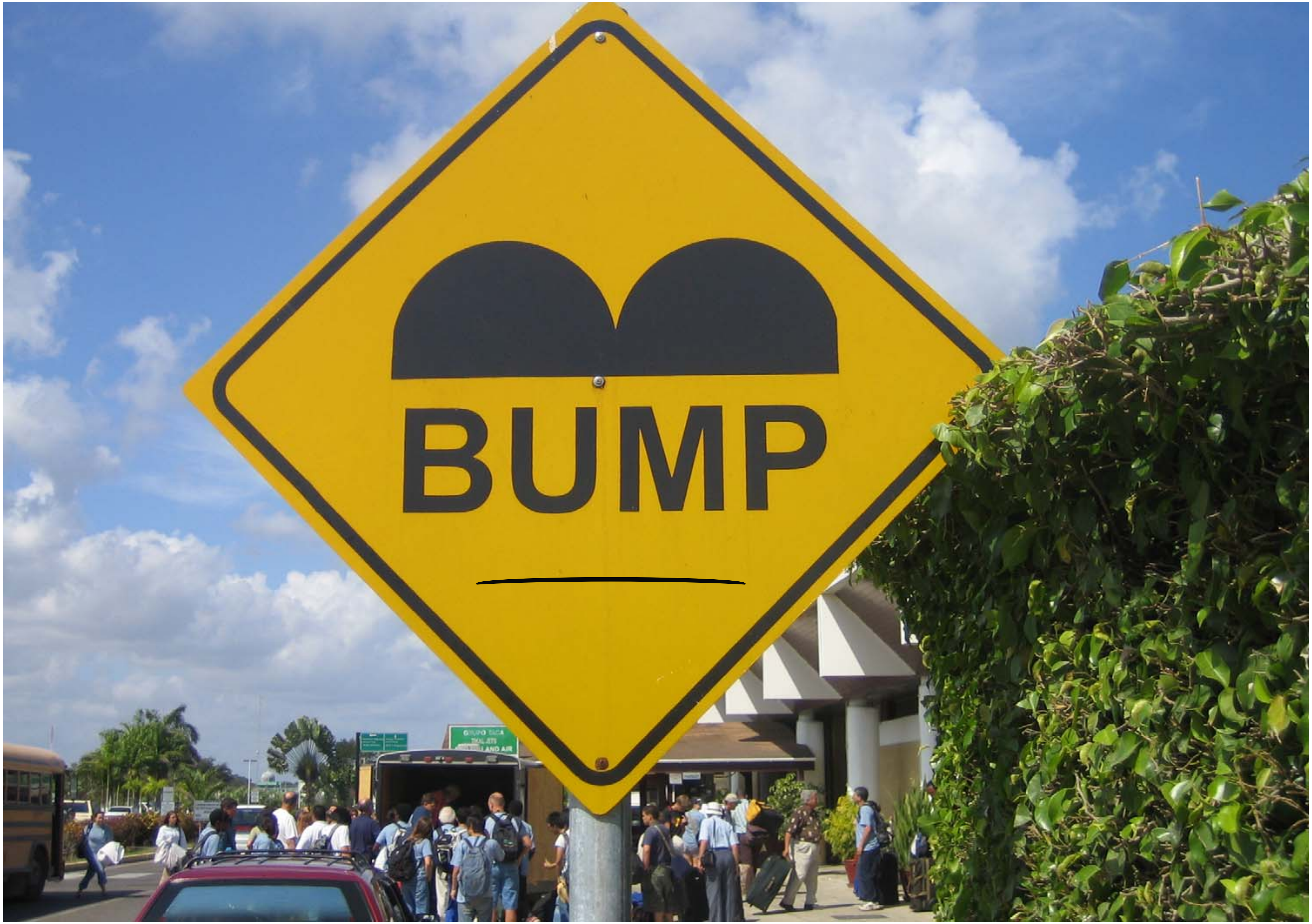
$$M_T^2 = 2\,|P_T^{\mu}|\,|P_T^{\upsilon}|\,(1 - \cos\Delta\phi_{\mu\upsilon})$$

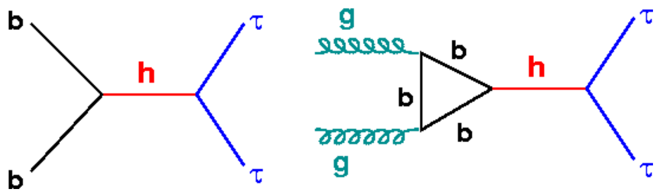
CDF Run II Preliminary





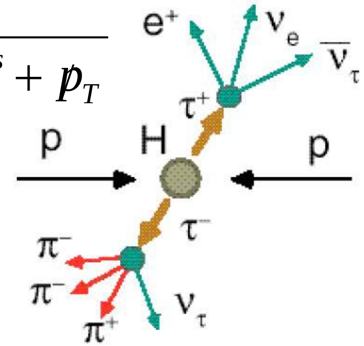
Jacobian Peak


BUMP

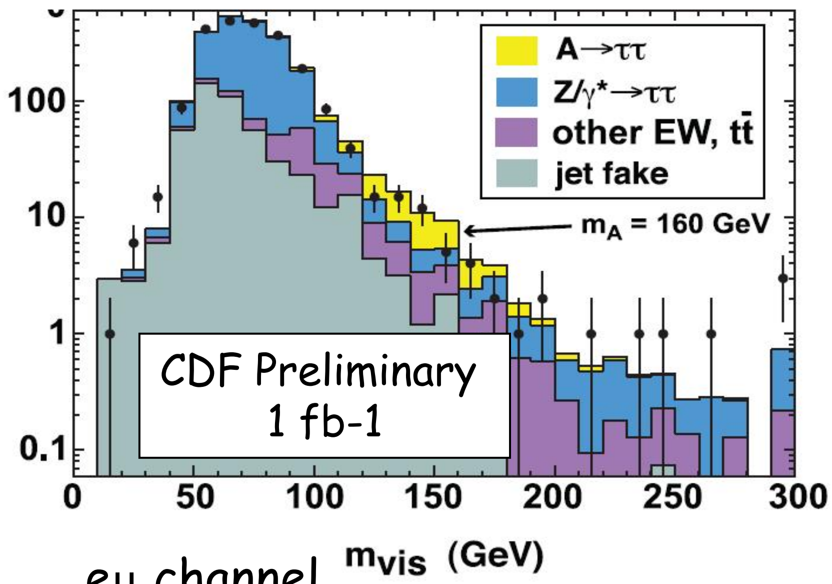


φ–>ττ

$$m_{vis} = \sqrt{p_{\tau_1}^{vis} + p_{\tau_2}^{vis} + \not{p}_T}$$



eτ,μτ channel



2 tau candidates

One hadronic or leptonic (CDF) decay

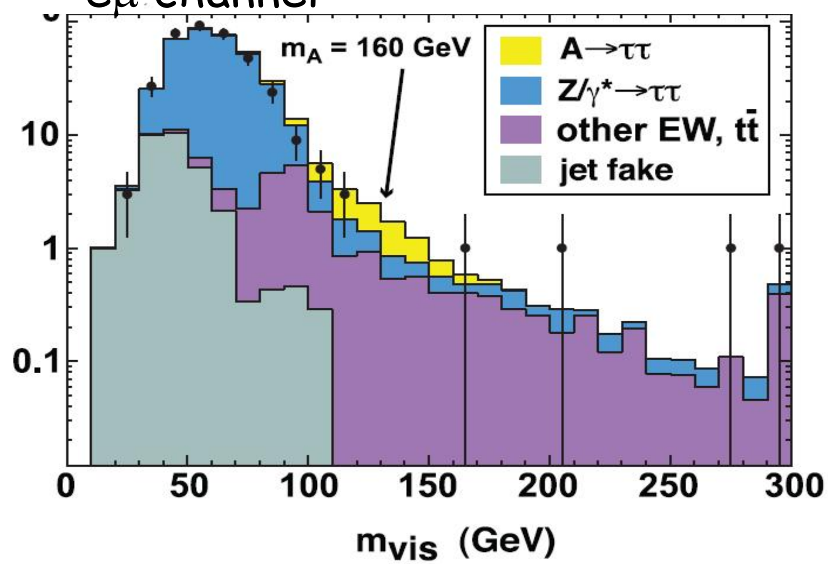
One leptonic decay (opposite charge)

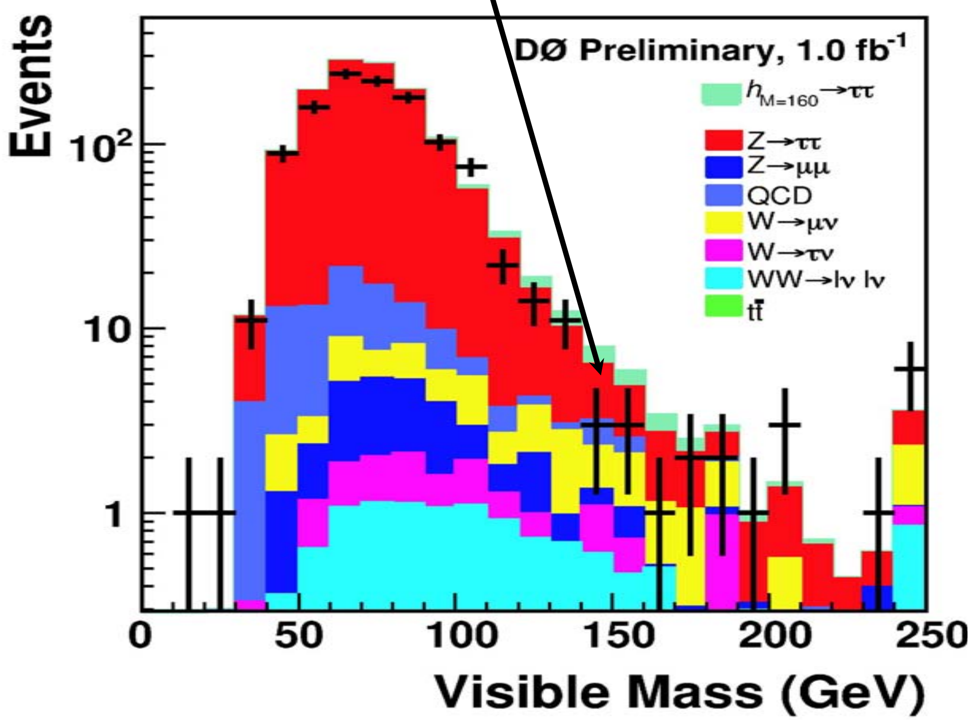
(CDF: e,μ) (D0: μ)

small excess in CDF eτ+μτ channel (<2σ effect)

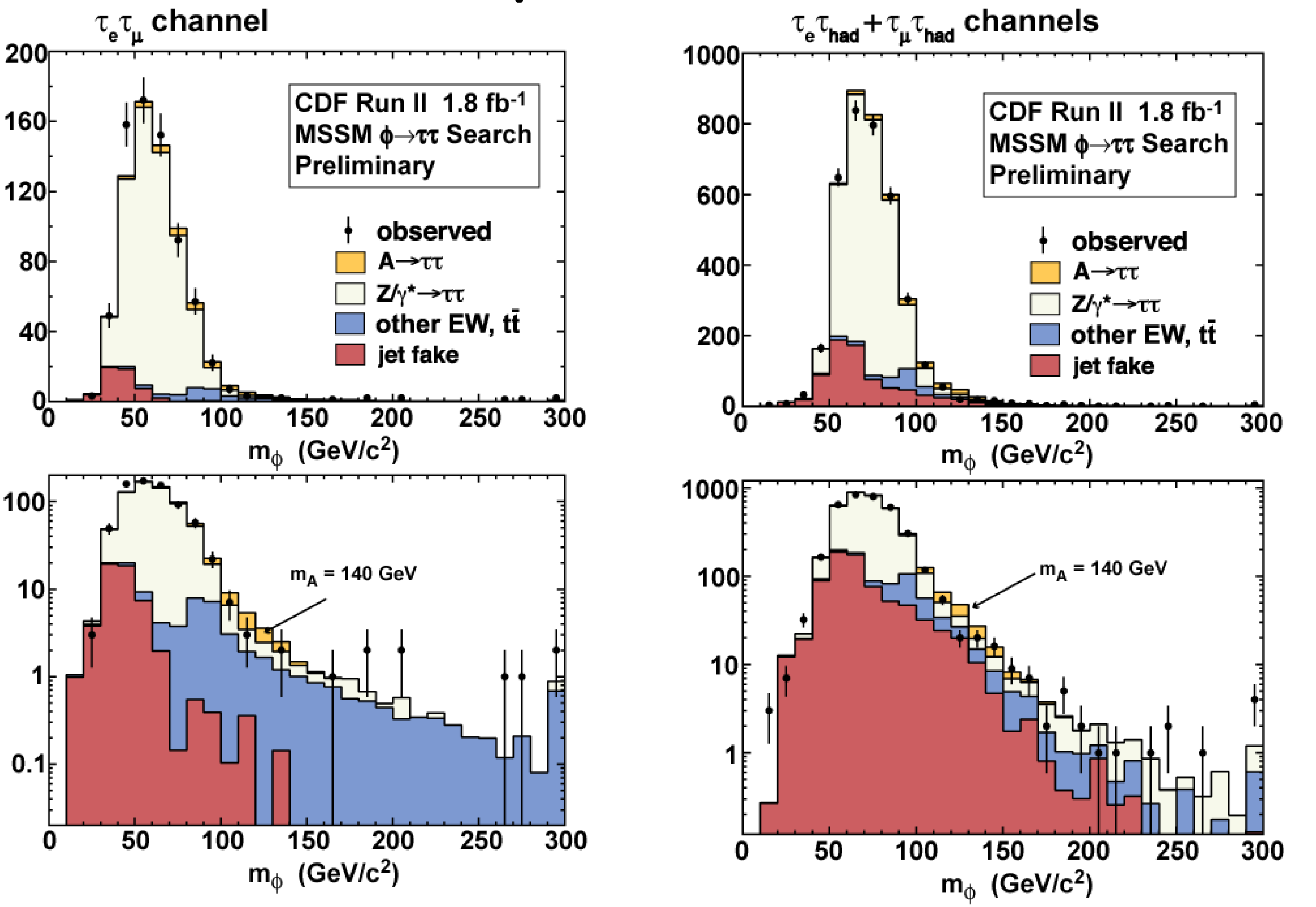
- Not observed in CDF eμ channel
- D0 analysis in good agreement with SM

eμ channel

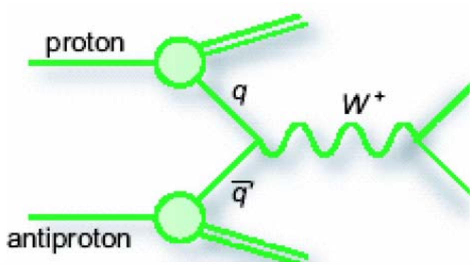


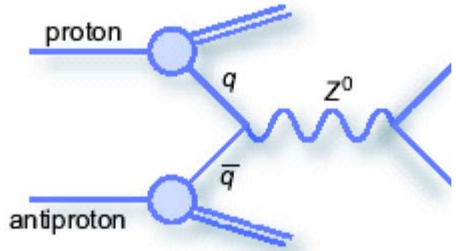


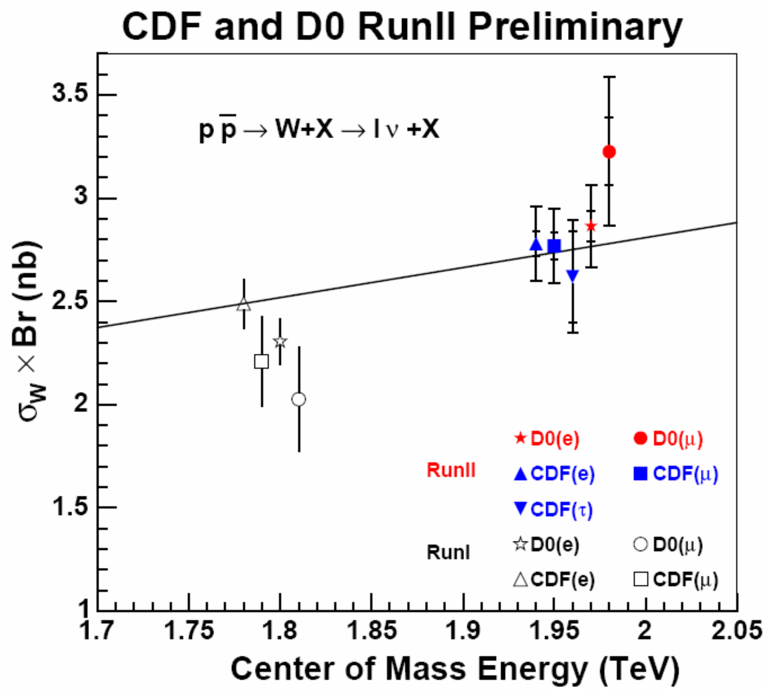
No Bump with 1.8 fb^{-1}!

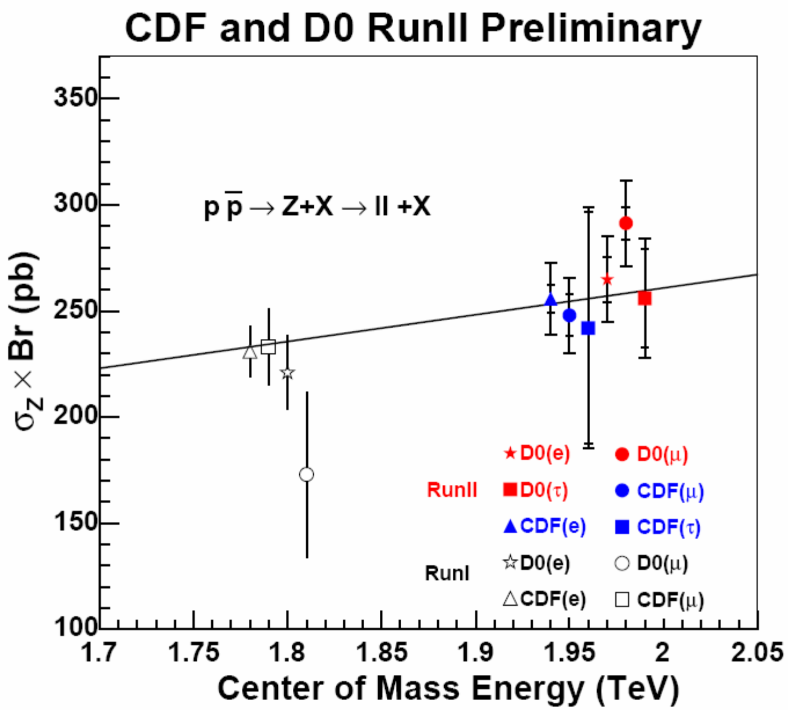


W & Z Production Cross Section





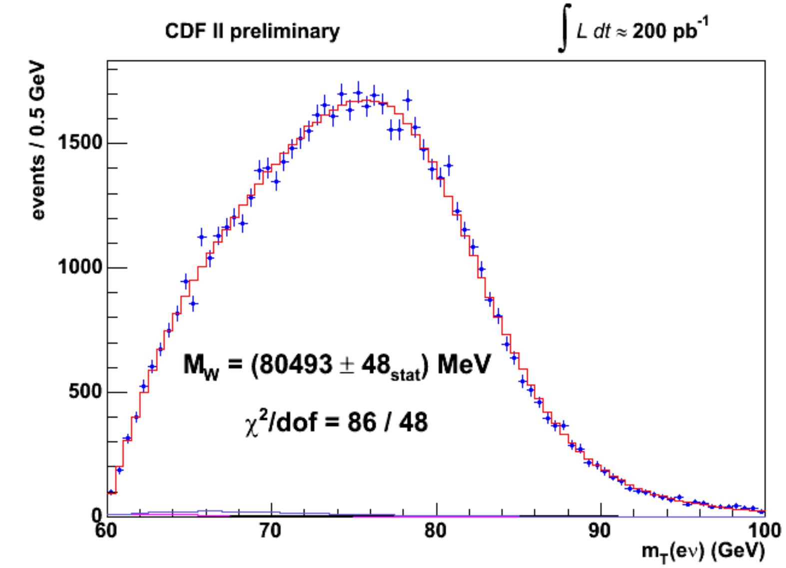


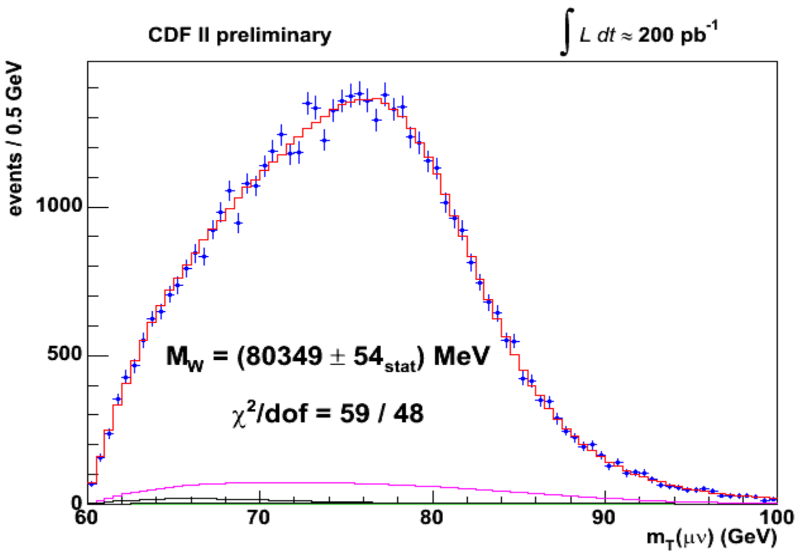


$$\sigma = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{q'}(x_2, Q^2) \hat{\sigma}_{qq' \to l^+ l^-}$$

NNLO pQCD calculation describes the data very well…

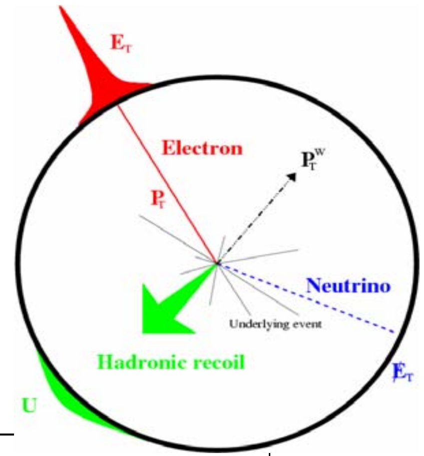
W Mass

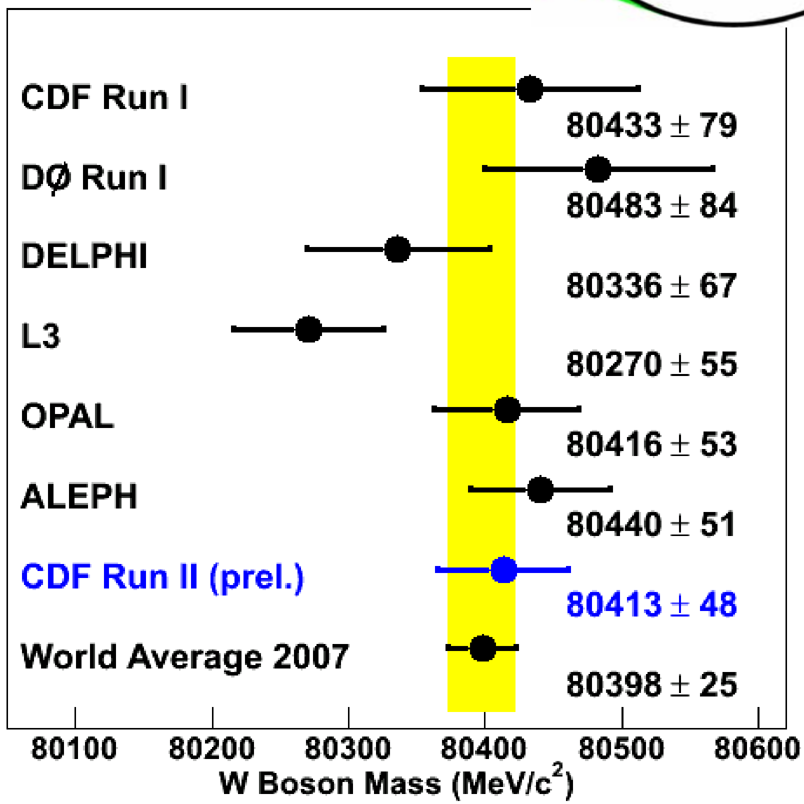




$$m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$

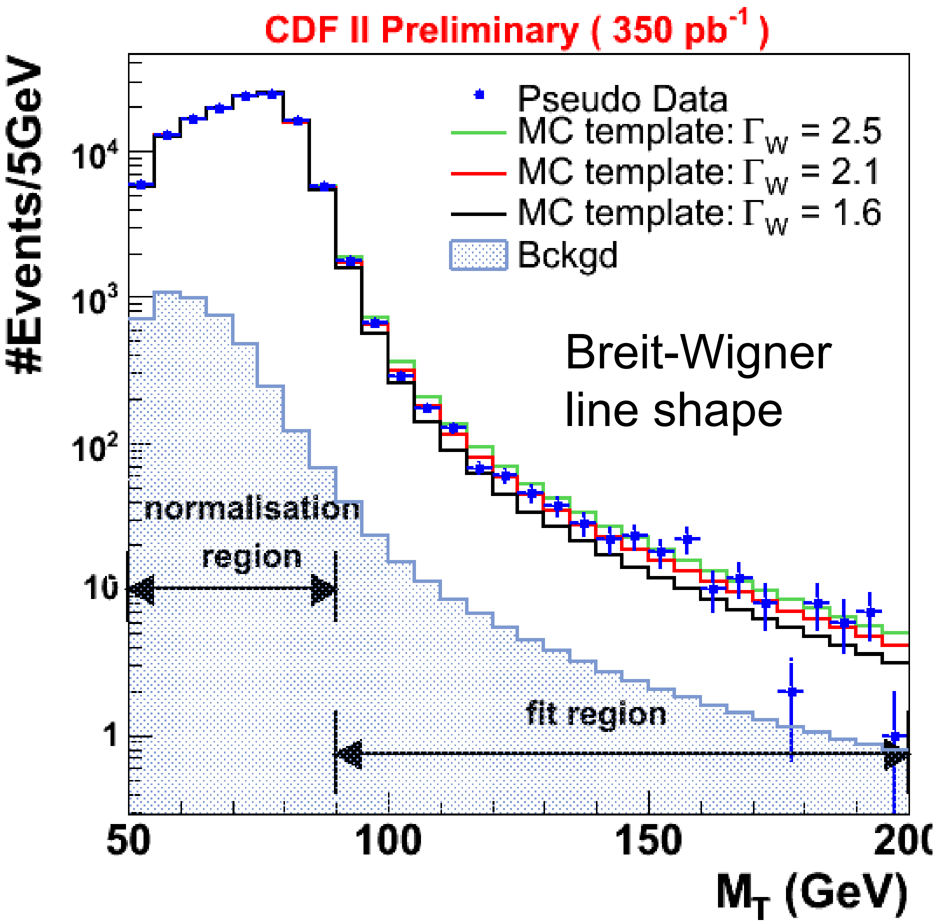
Detailed Modeling of Hadronic Recoil carefully studied using Zs and Ws

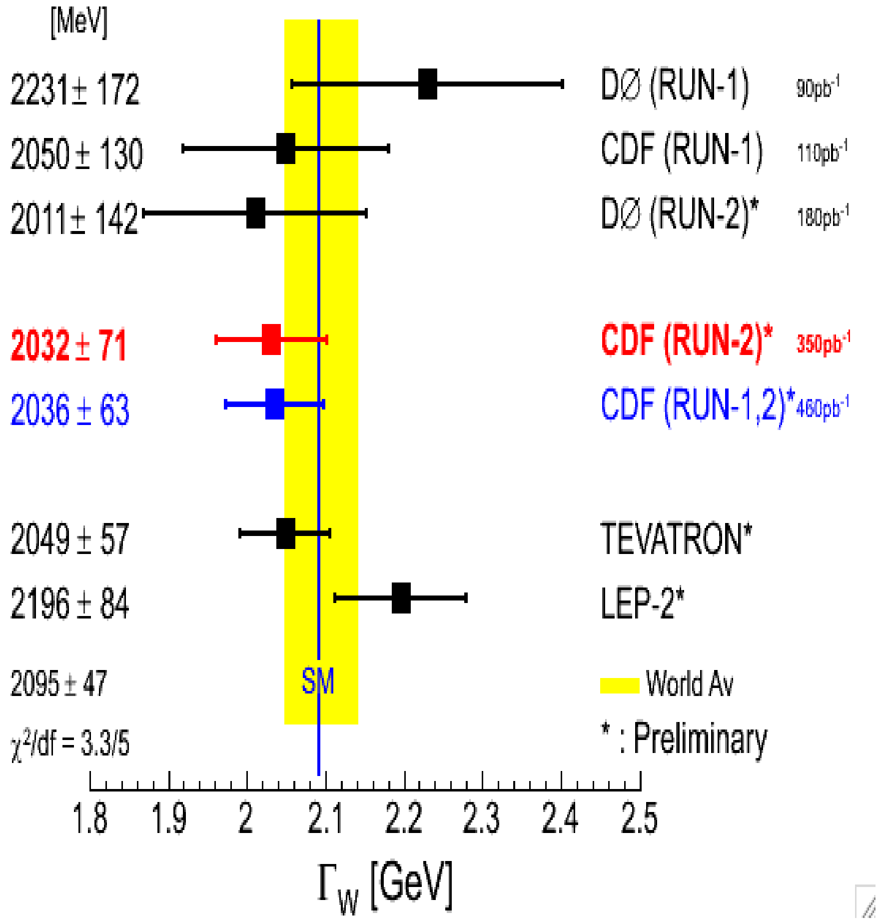




M_W = 80413 ± 48 MeV/c^2
(the world's most precise single measurement)

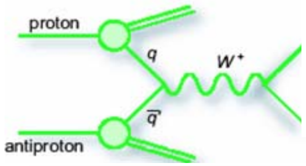
W width



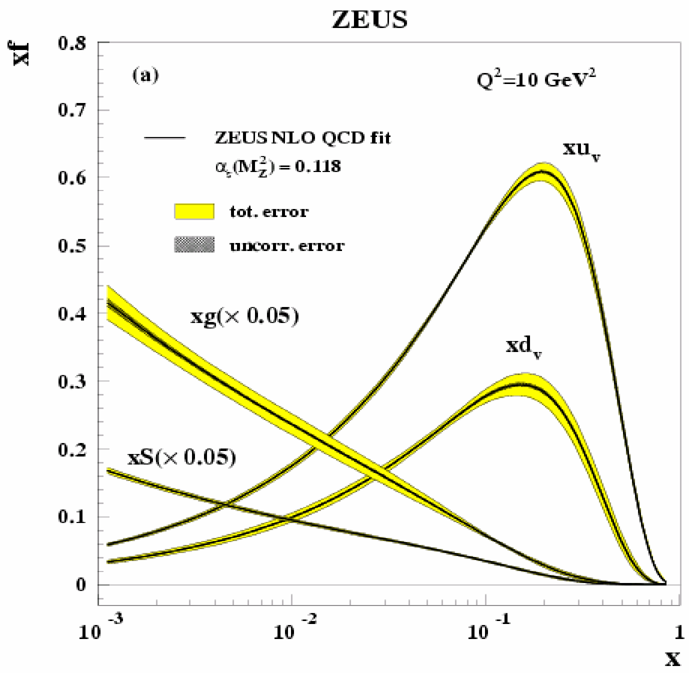


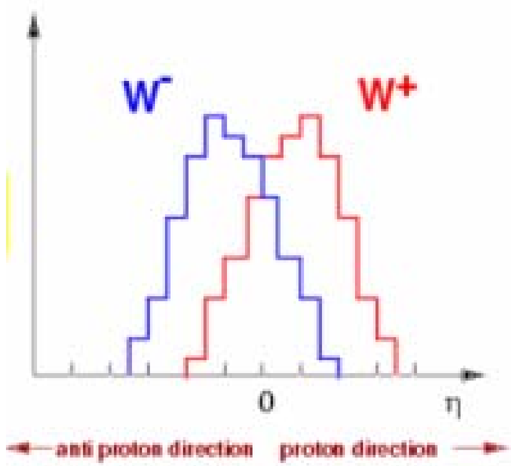
Γ_W = 2032 ± 71 (stat + syst) MeV

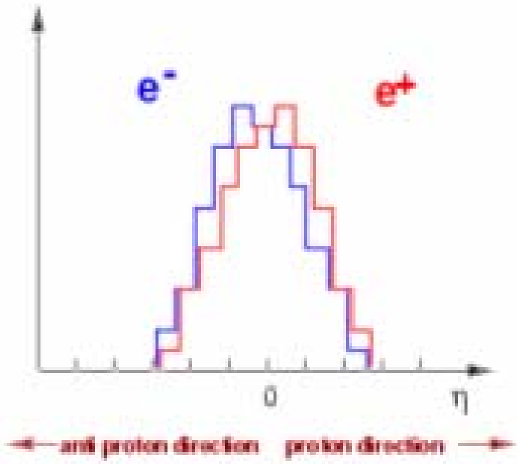
(the world's most precise single measurement)



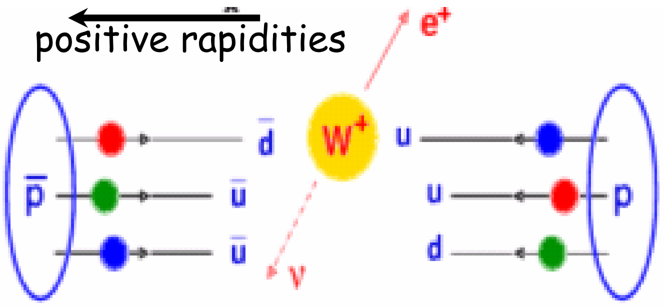
W Charge Asymmetry

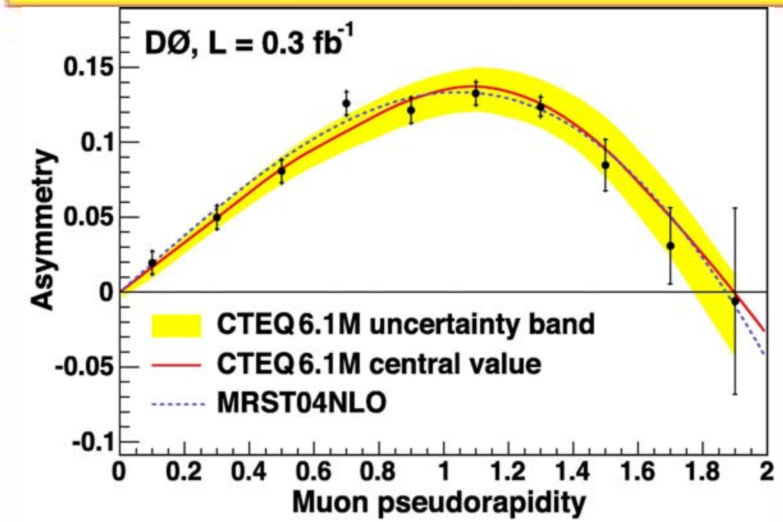






$$A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta} \simeq \frac{d(x)}{u(x)}$$

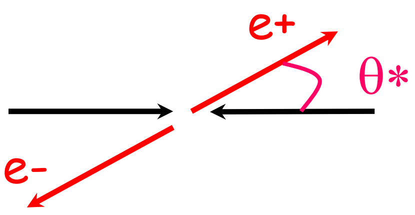




W+ boosted towards proton direction (+η)

A_{FB} asymmetry ($Z^0 \to e^+e^-$)

- Forward-Backward Asymmetry



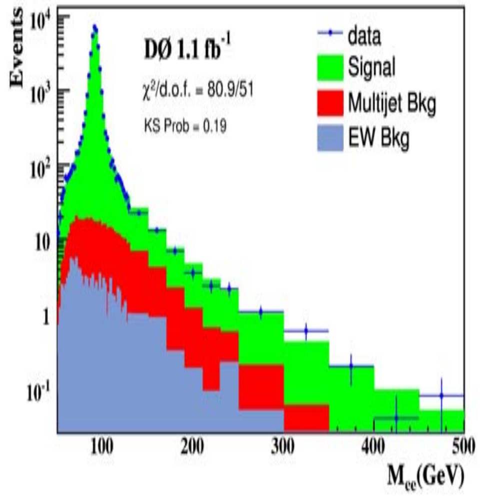
$$A_{FB} = \frac{d\sigma(\cos\theta > 0) - d\sigma(\cos\theta < 0)}{d\sigma(\cos\theta > 0) + d\sigma(\cos\theta < 0)}$$

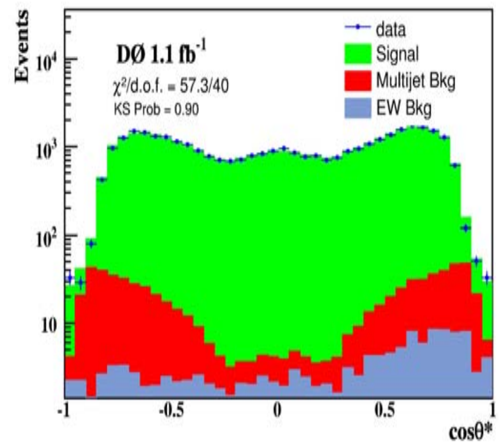
- Direct probe of γ,Z couplings (sensitive to new physics)

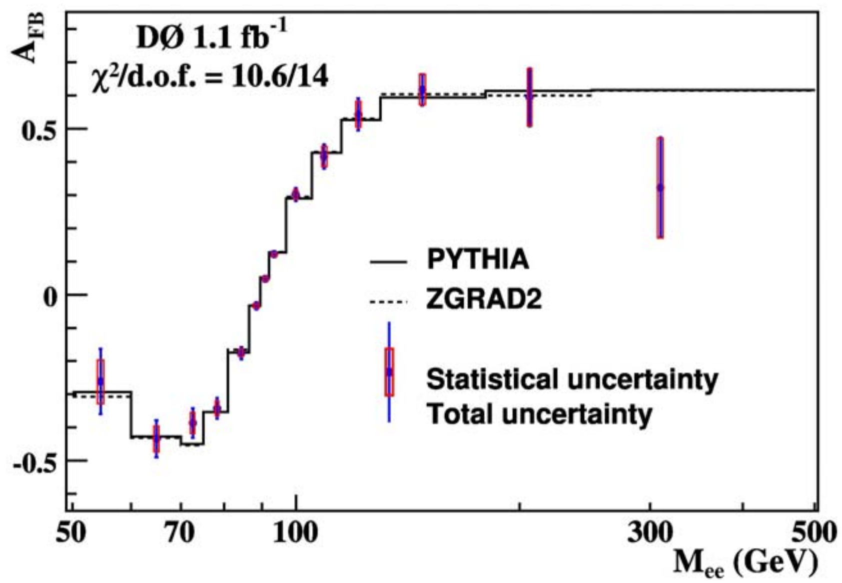
- High mass unique to Tevatron

- Results consistent with SM

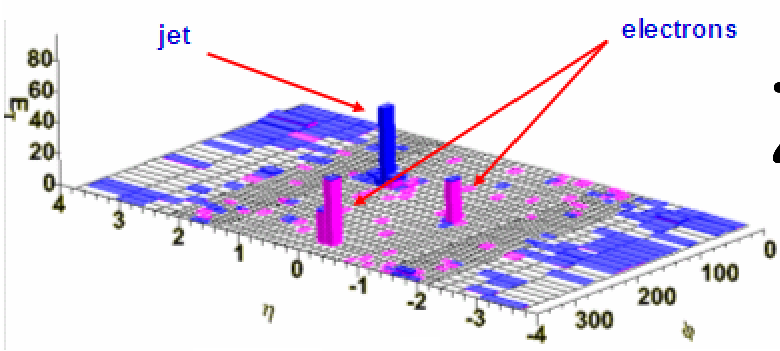
...waiting for more data...

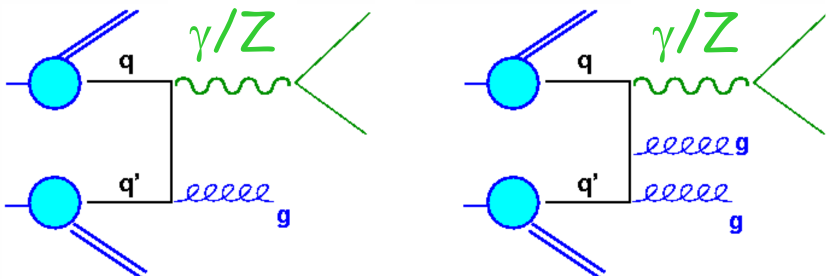


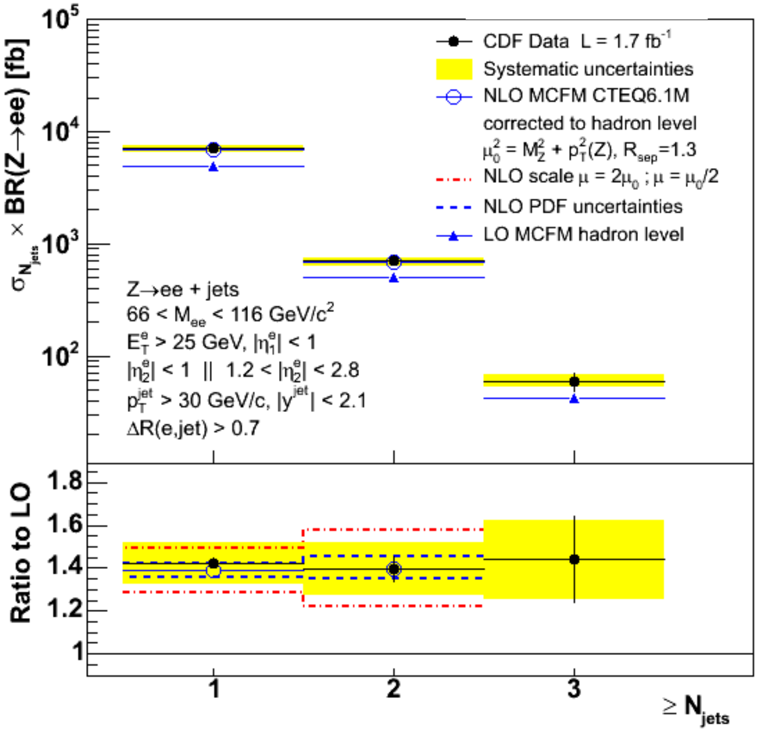


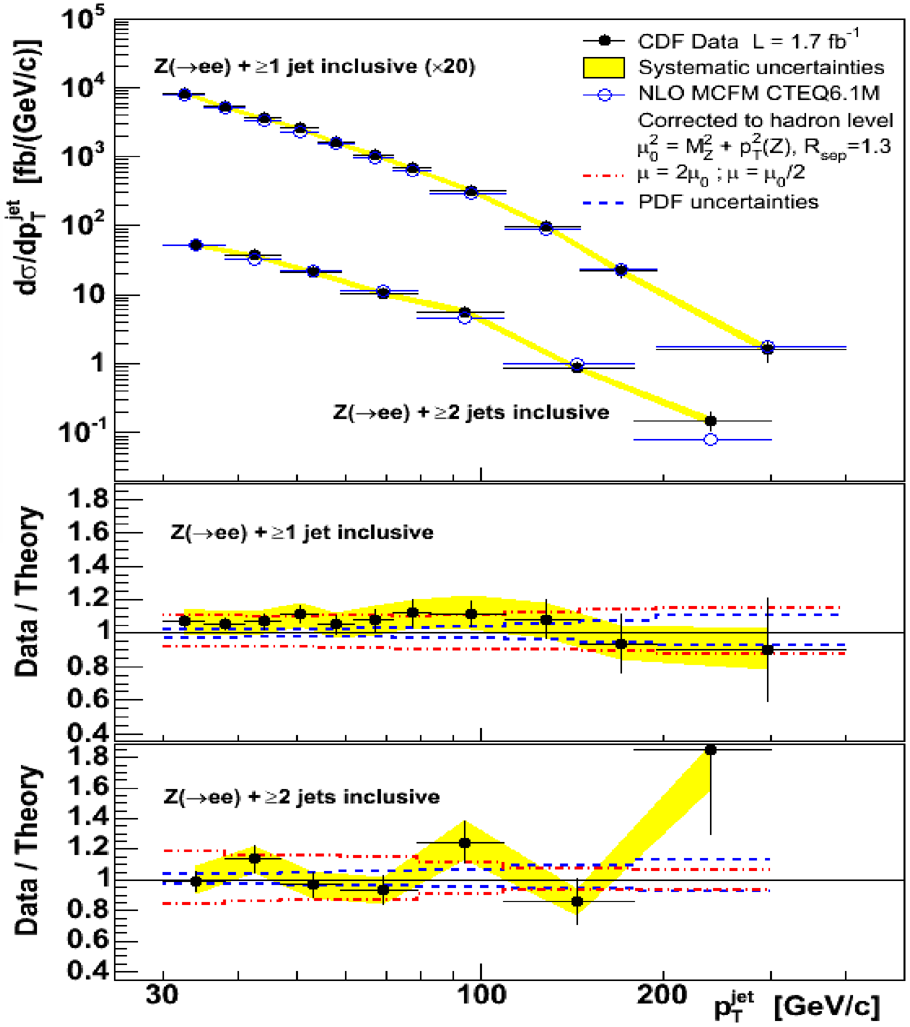


Z/γ*+jet(s) Production



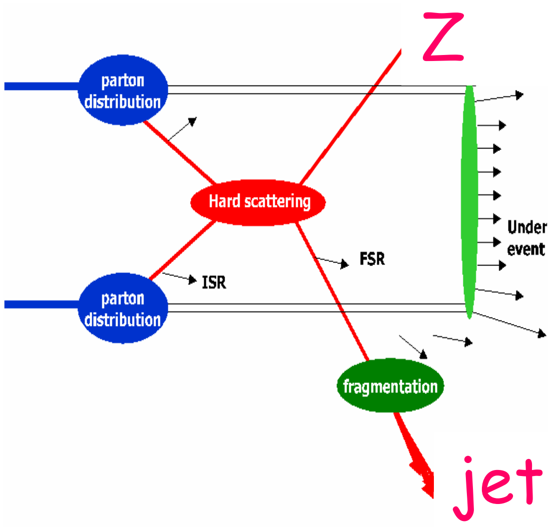


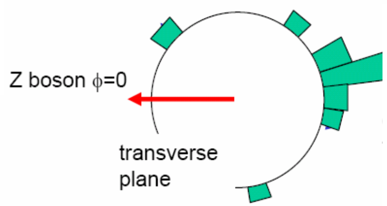


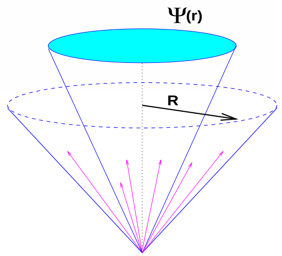


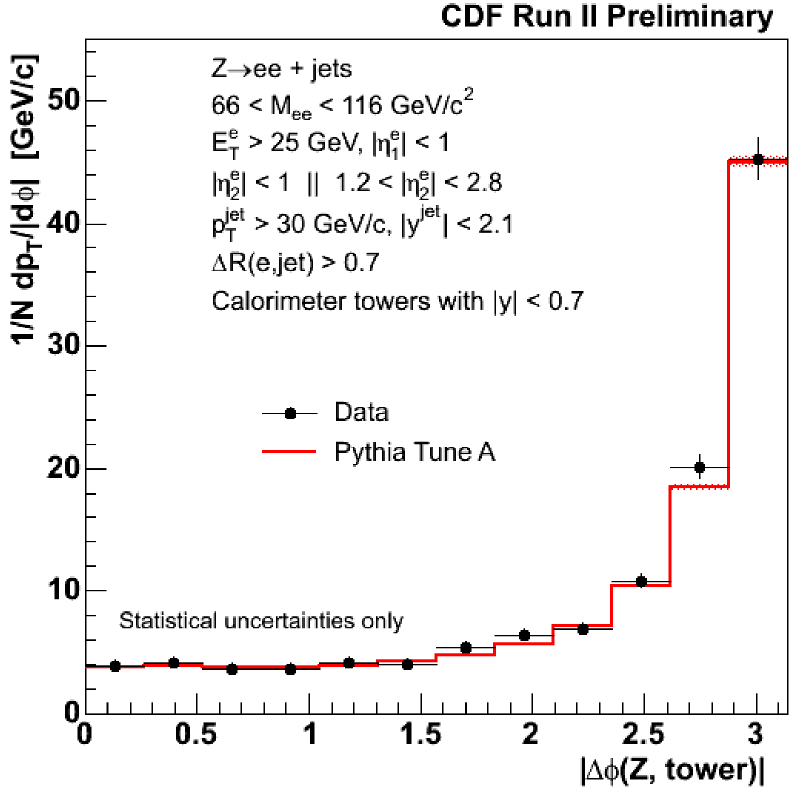
Good agreement with NLO pQCD predictions

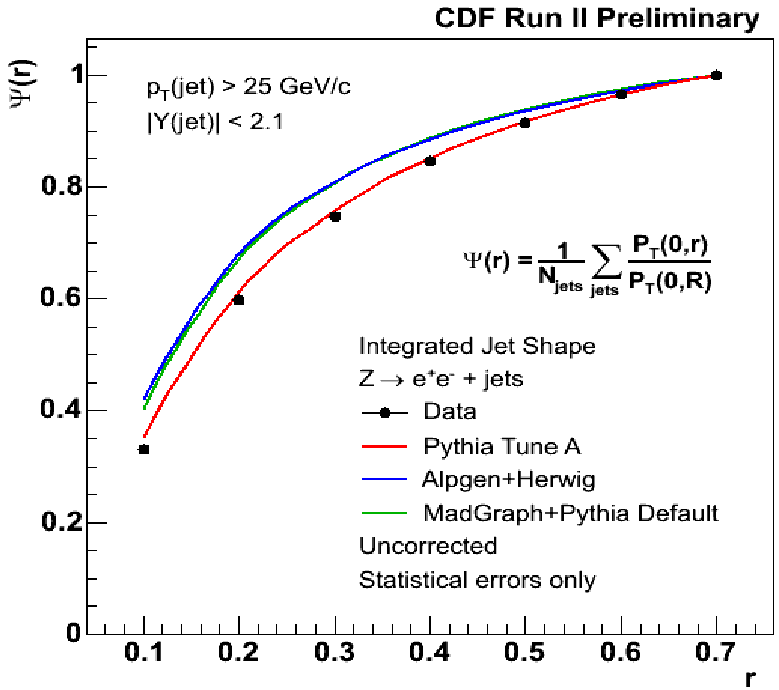
Soft radiation in Z+jet(s)







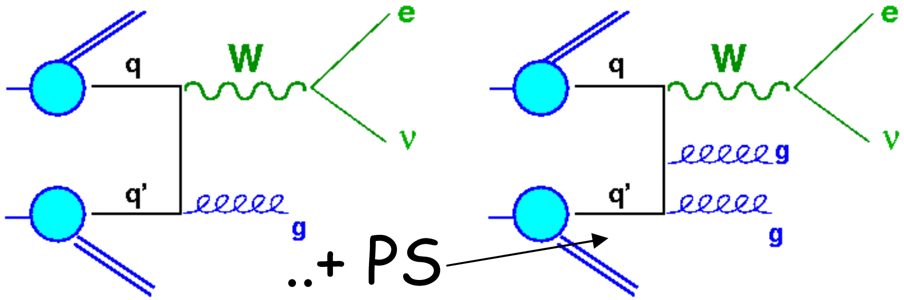




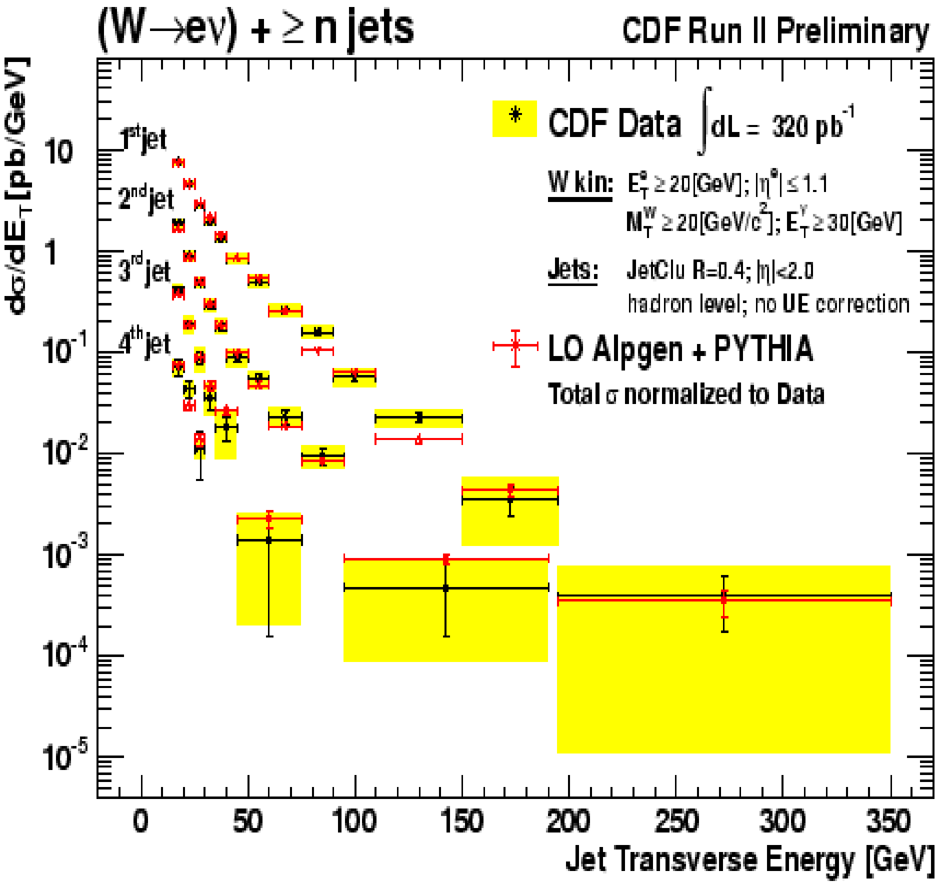
Implementation of proper modeling of UE still needed in new W/Z+Jet(s) Monte Carlos....very important

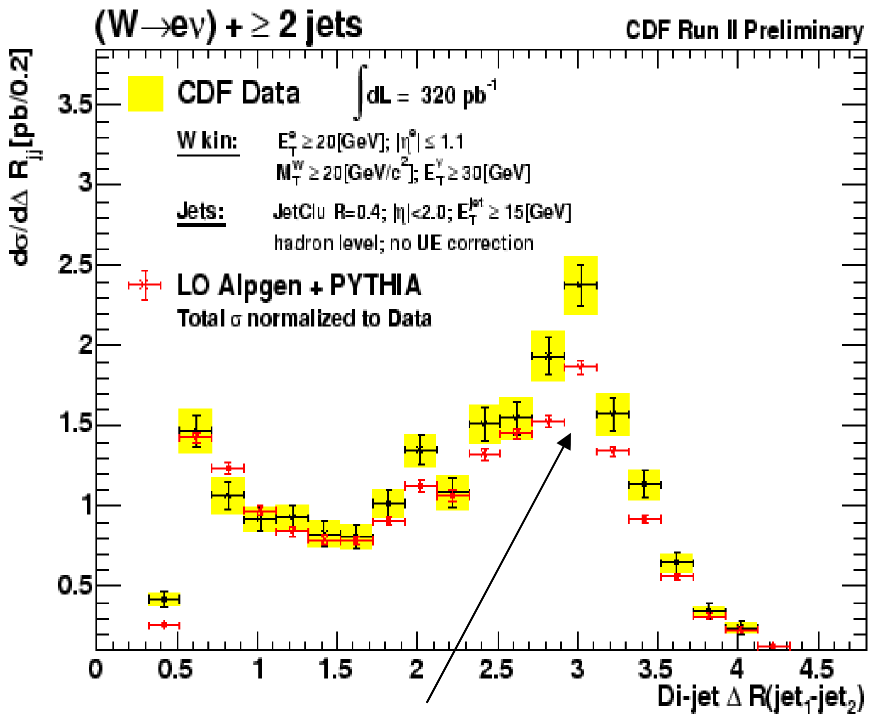
LHC will use "extra jets" veto in Higgs analyses to reduce QCD bckg.

W+jet(s) Production



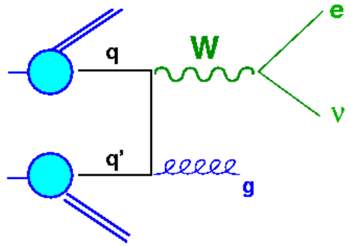
- Background top, Higgs, SUSY…
- Stringent test of pQCD predictions
- Test Ground for ME+PS techniques
  (Special matching → MLM, CKKW to avoid double counting on ME+PS interface)

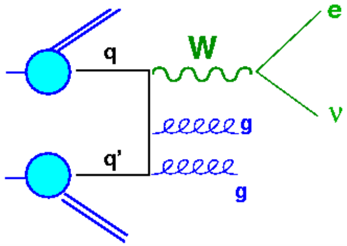


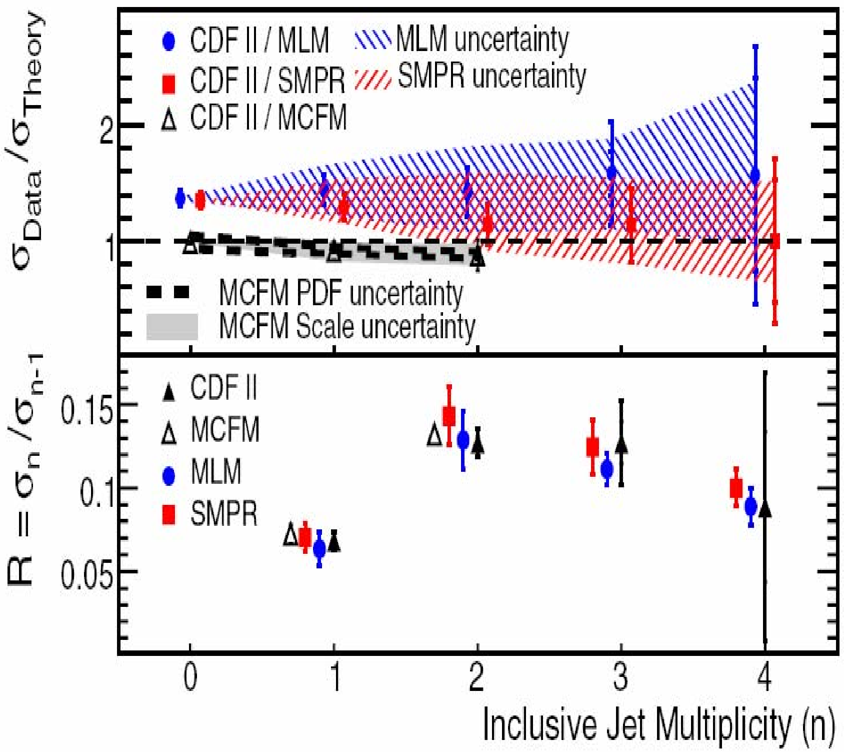


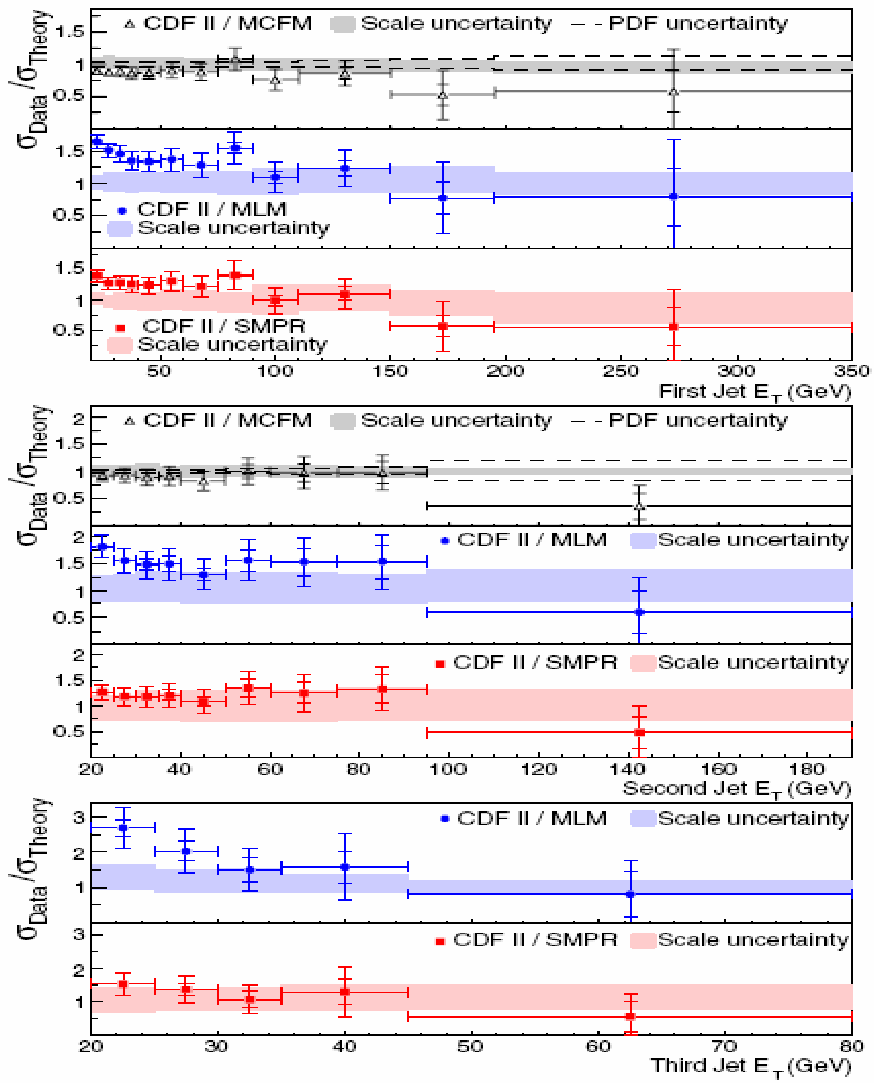
Affected by cutoff and soft radiation

W+jet(s) Production



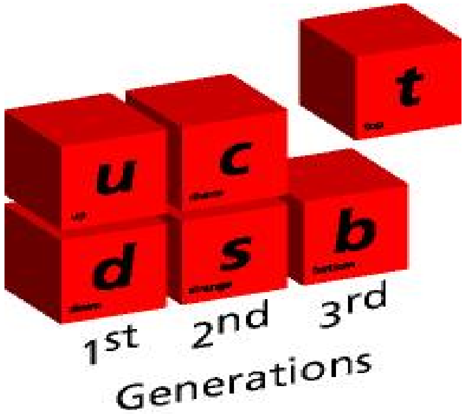




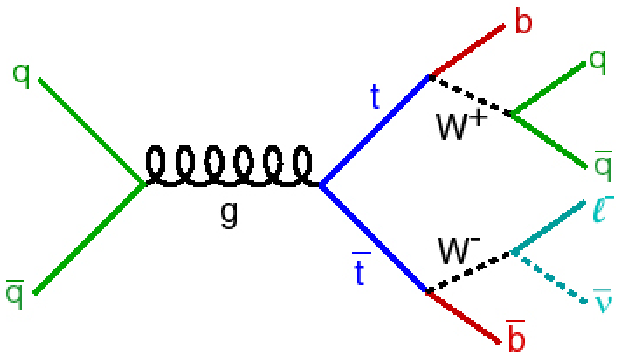


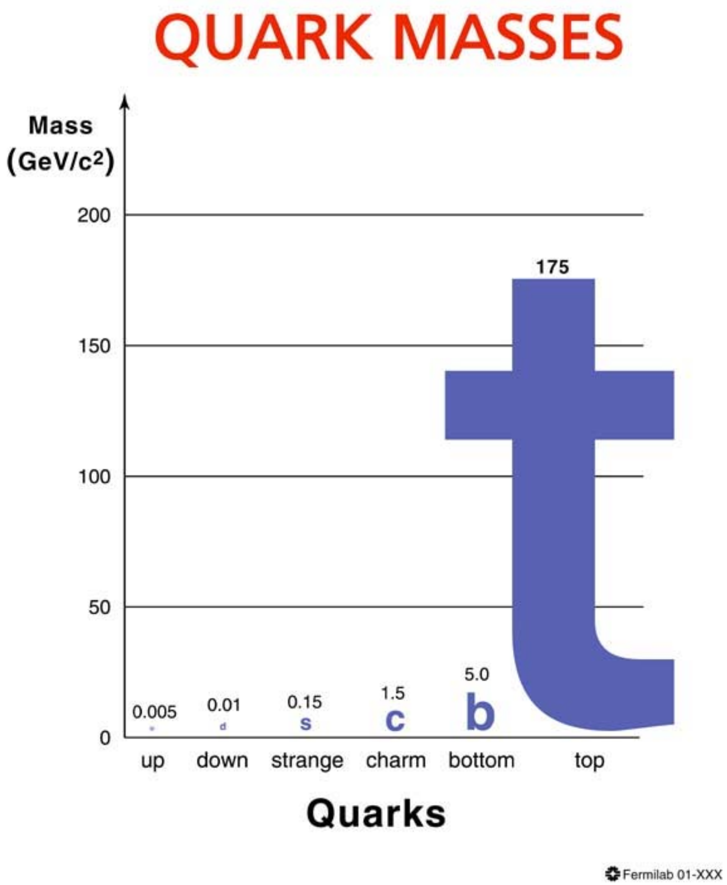
Good agreement with pQCD NLO calculation (includes non-pQCD effects)

At low P_T Monte Carlo needs a better modeling of UE (ALPGEN+PYTHIA)



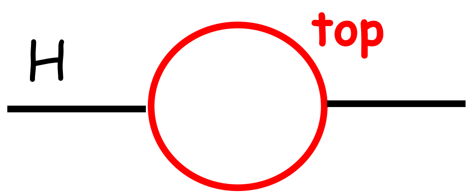
Top Quark





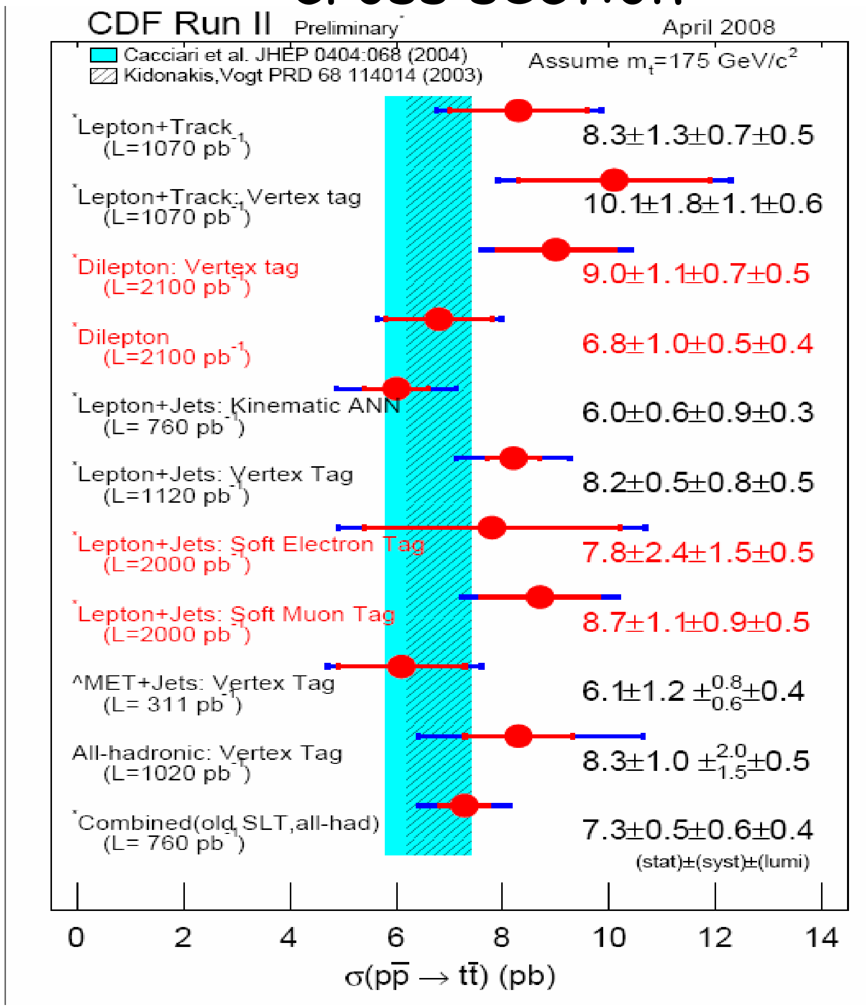
- Top quark is unusually massive
  - as heavy as a gold atom yet elementary
  - ~40 times heavier than b quark
- Decays before it hadronizes
  - The only 'bare' quark we can observe
- Yukawa coupling to Higgs close to unity
  - Suggestive of a special role in EWSB
  - Key player in alternate mechanisms
- Large impact on radiative corrections
  - \- Constrains SM Higgs Mass

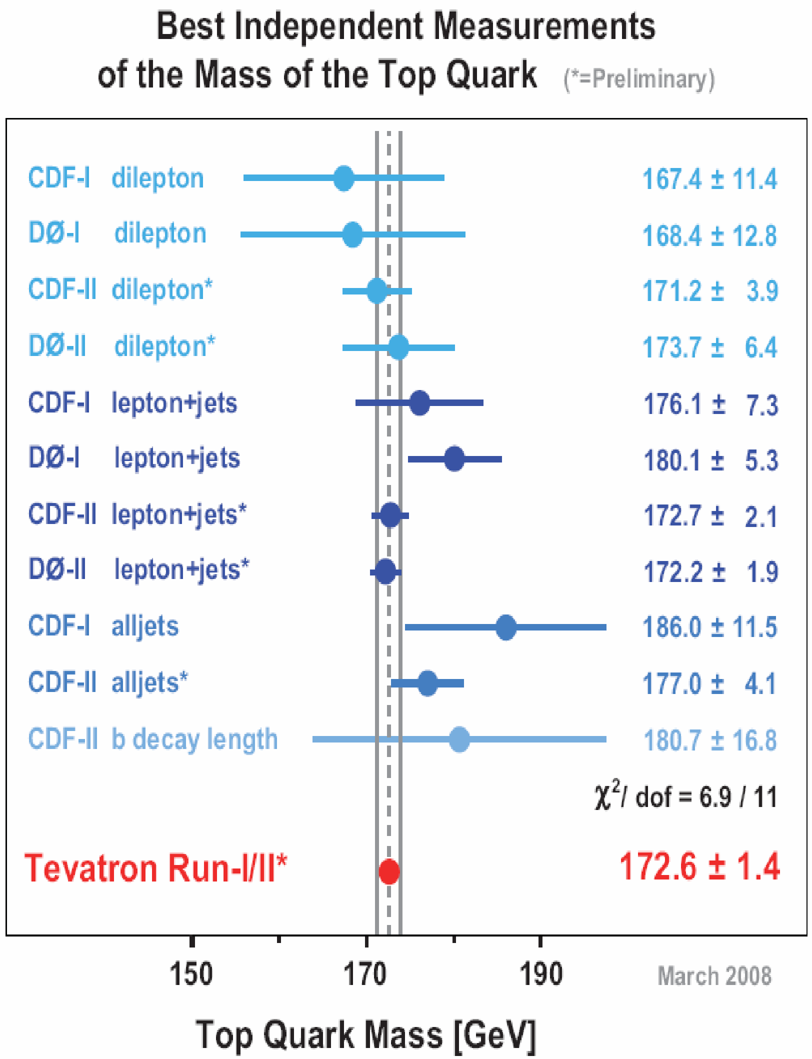
$$y_t = \frac{\sqrt{2}m_t}{v} \approx 1$$



Recent Top Quark Results

cross section

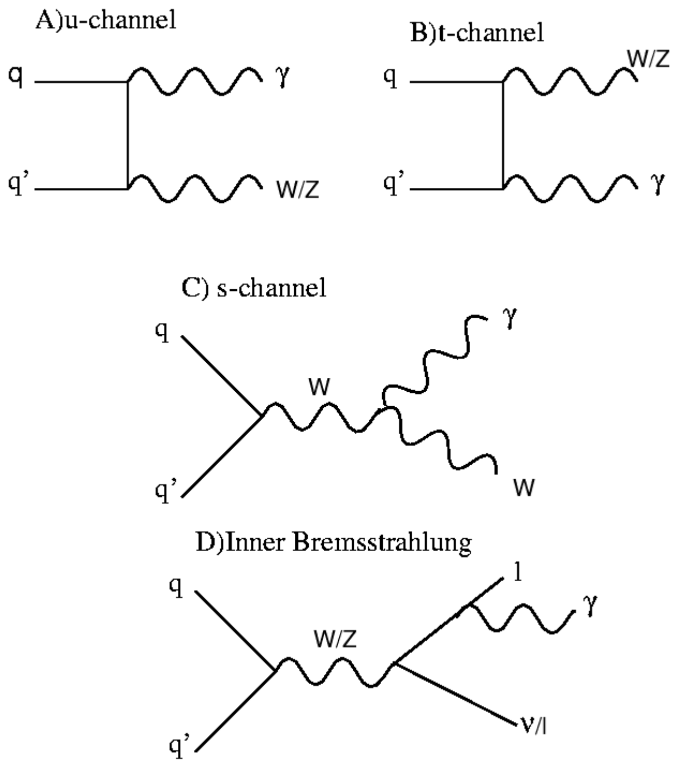


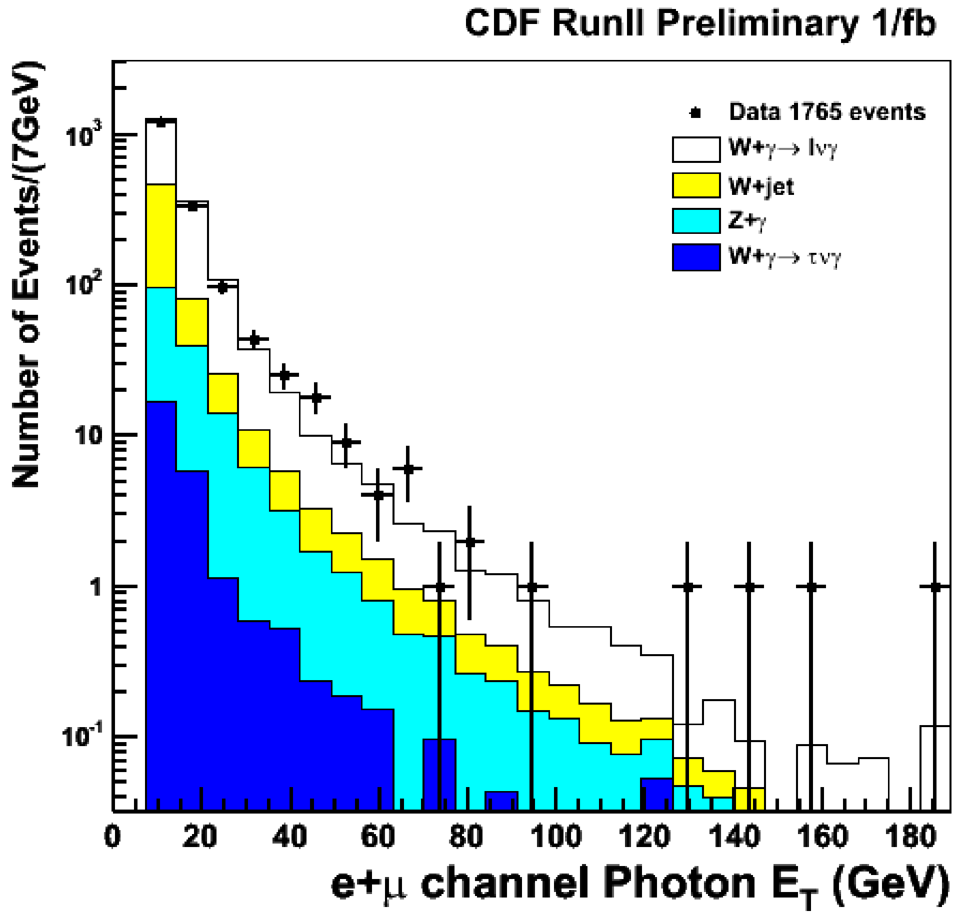


It looks like SM

relevant for Higgs searches

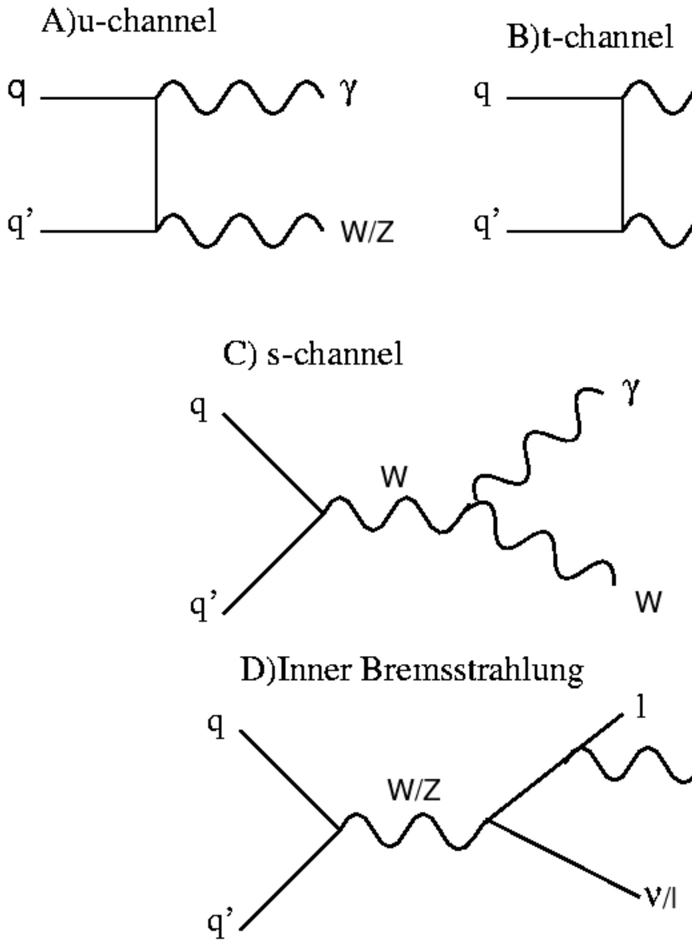
W+γ

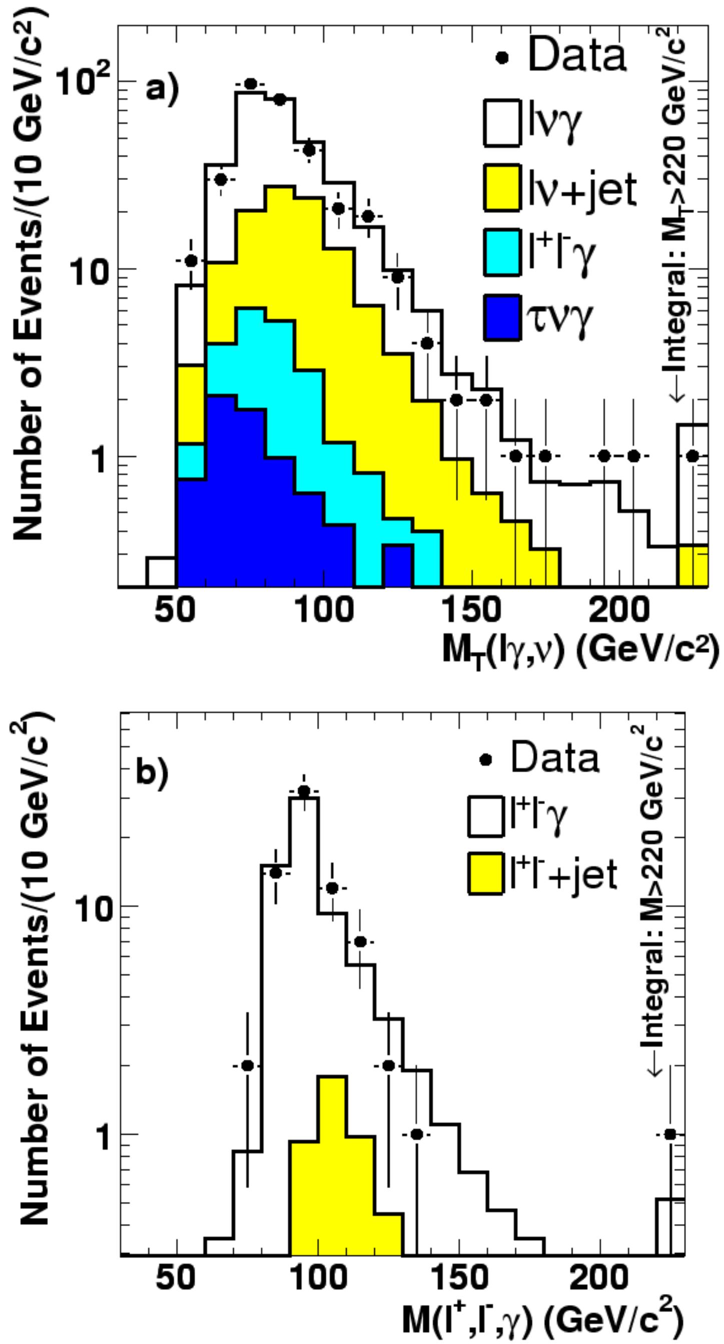




E_T photon > 7 GeV	CDF (pb)	NLO (pb)
$\sigma(W+\gamma)*B_R(W\to l\nu)$	18.03±0.65(stat)±2.55(sys) ±1.05(lum)	19.3±1.4

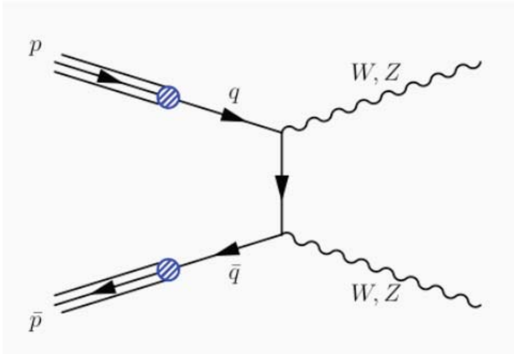
W/Z+γ

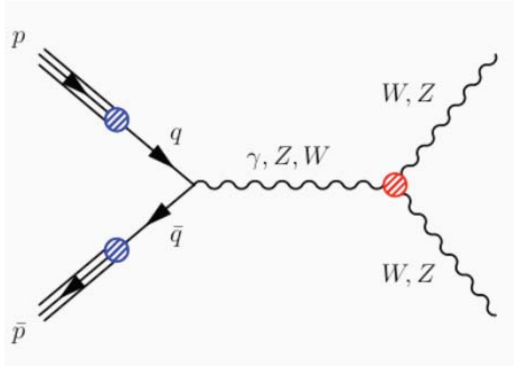


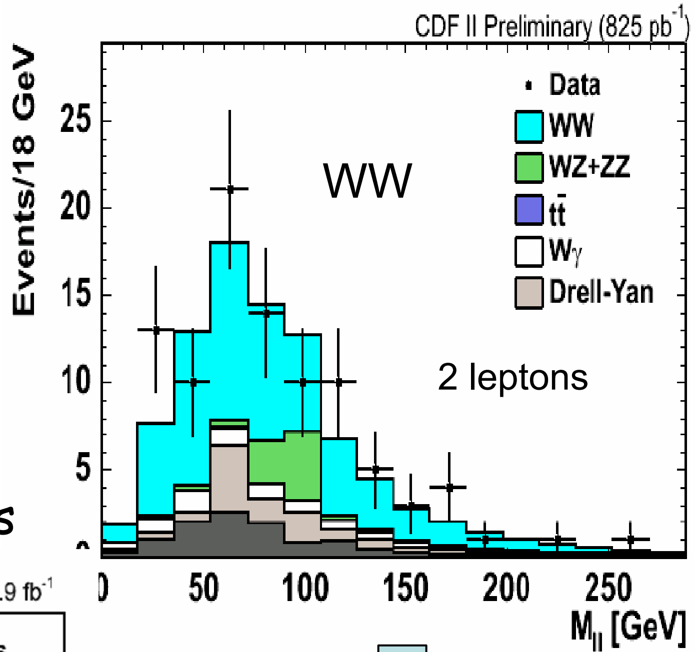


Good agreement with SM expectations

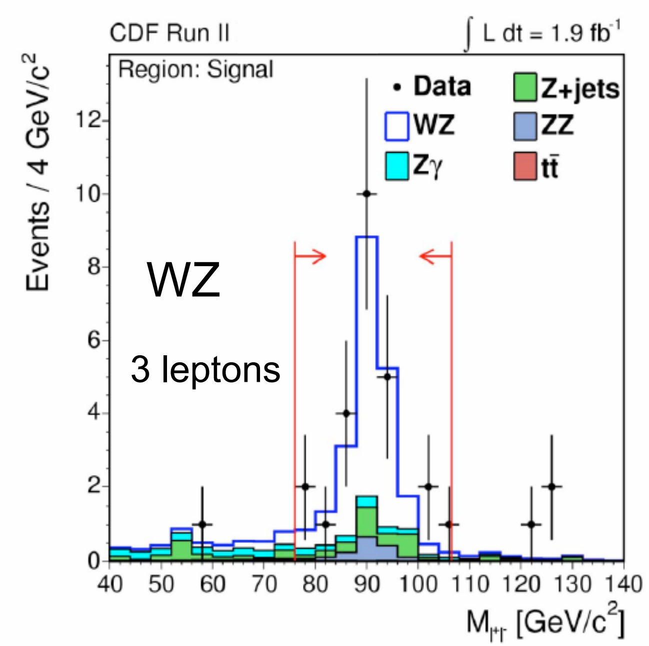
Diboson Production

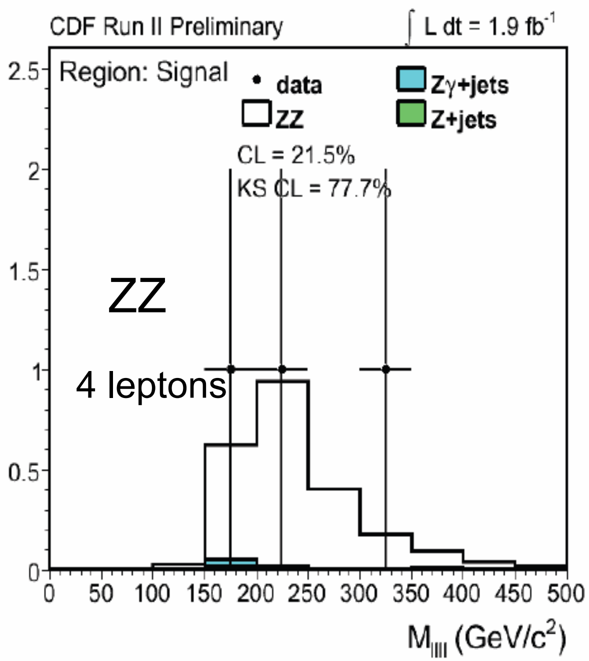






Searches carried out with different final states

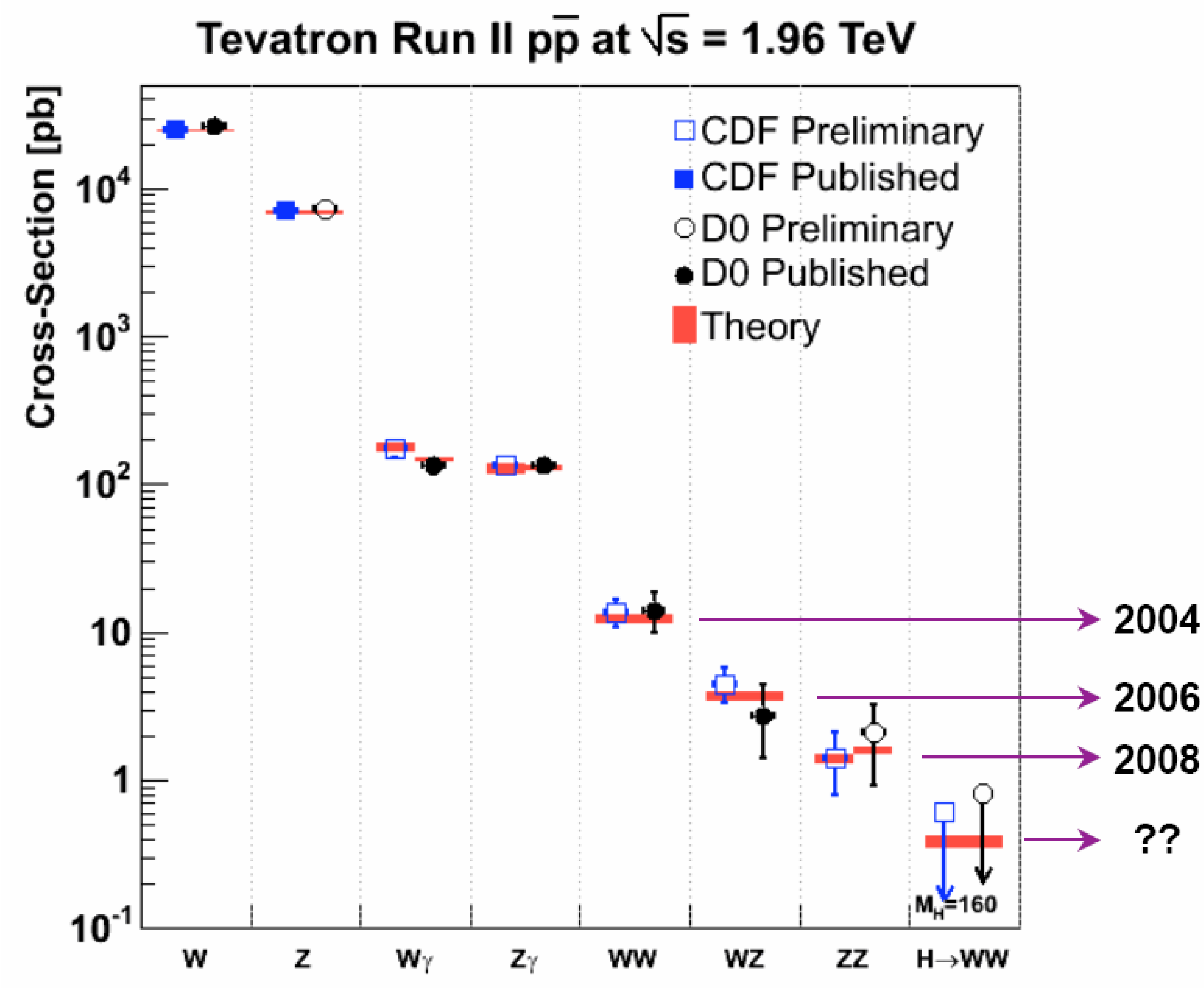




First Step towards Higgs

In good agreement with SM expectations

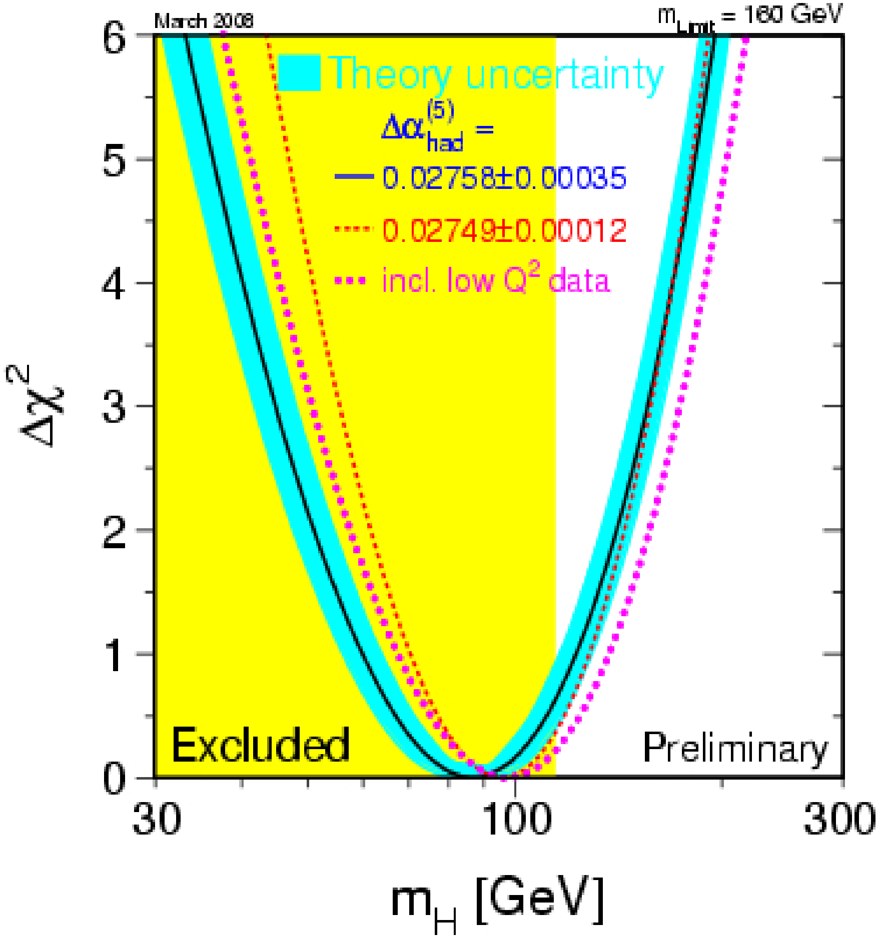
Summary of DiBoson Searches

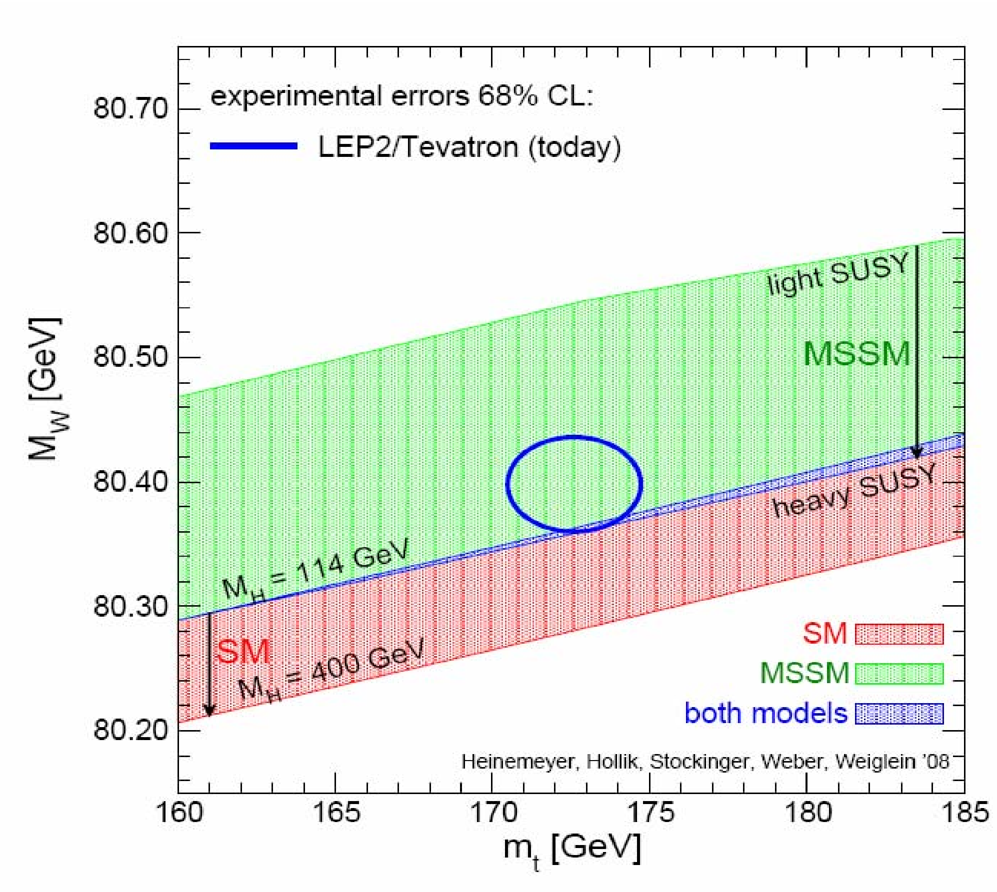


Electroweak Fits

(indirect Higgs Mass constrains)

H

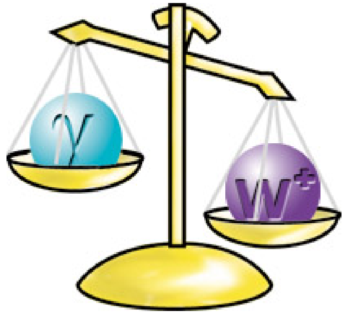




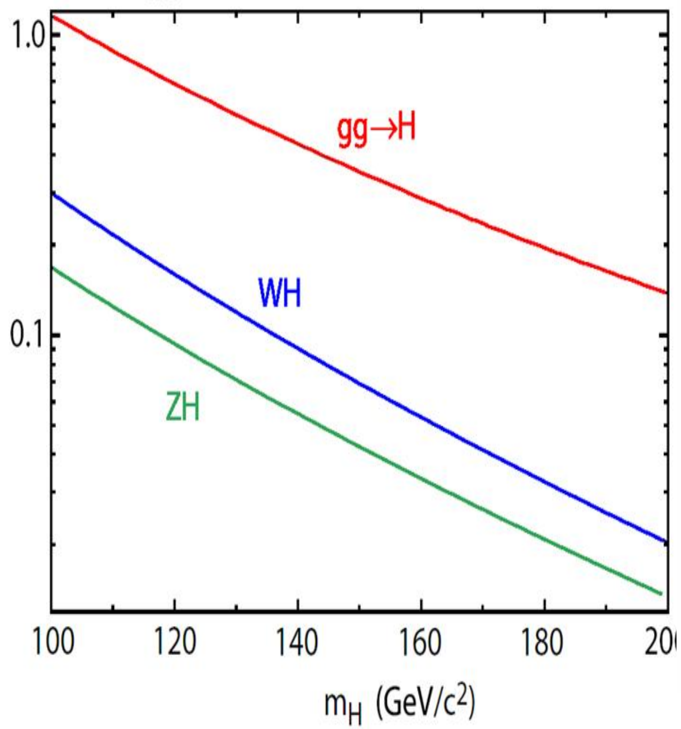
$$M_H < 190\ \mathrm{GeV}/c^2$$

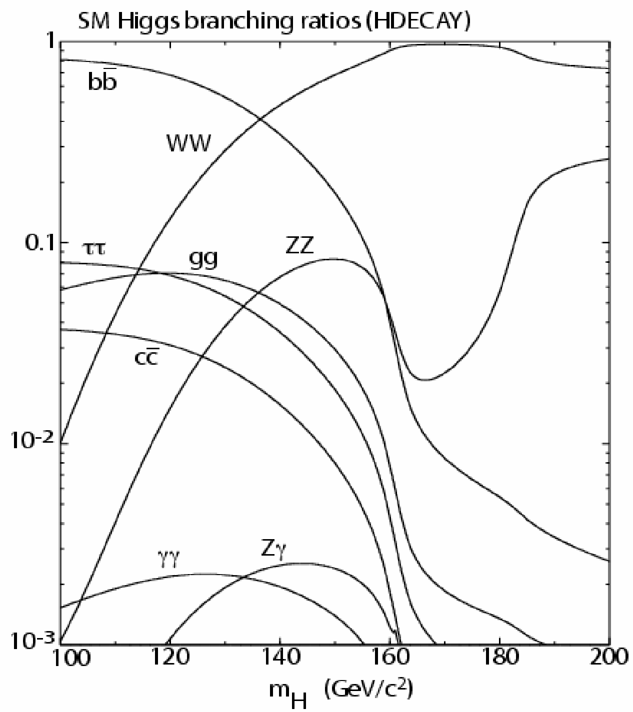
Measured top mass favors low values for M_H

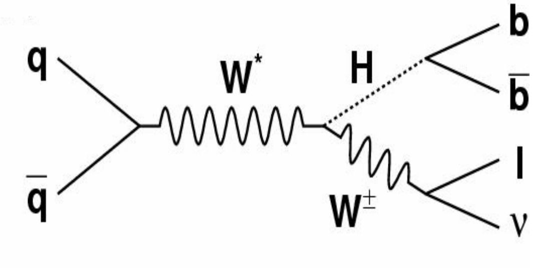
SM Higgs
(Direct searches)

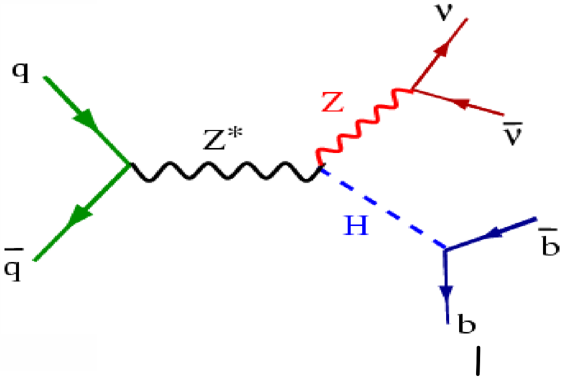


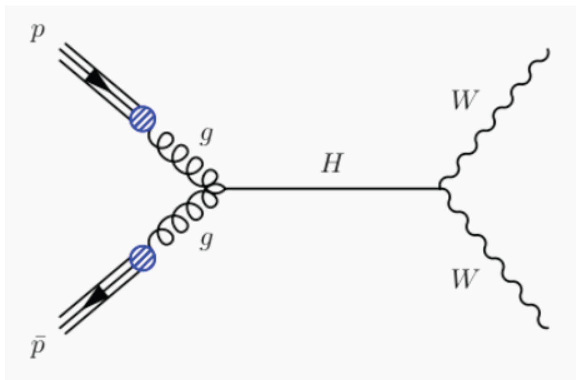
H







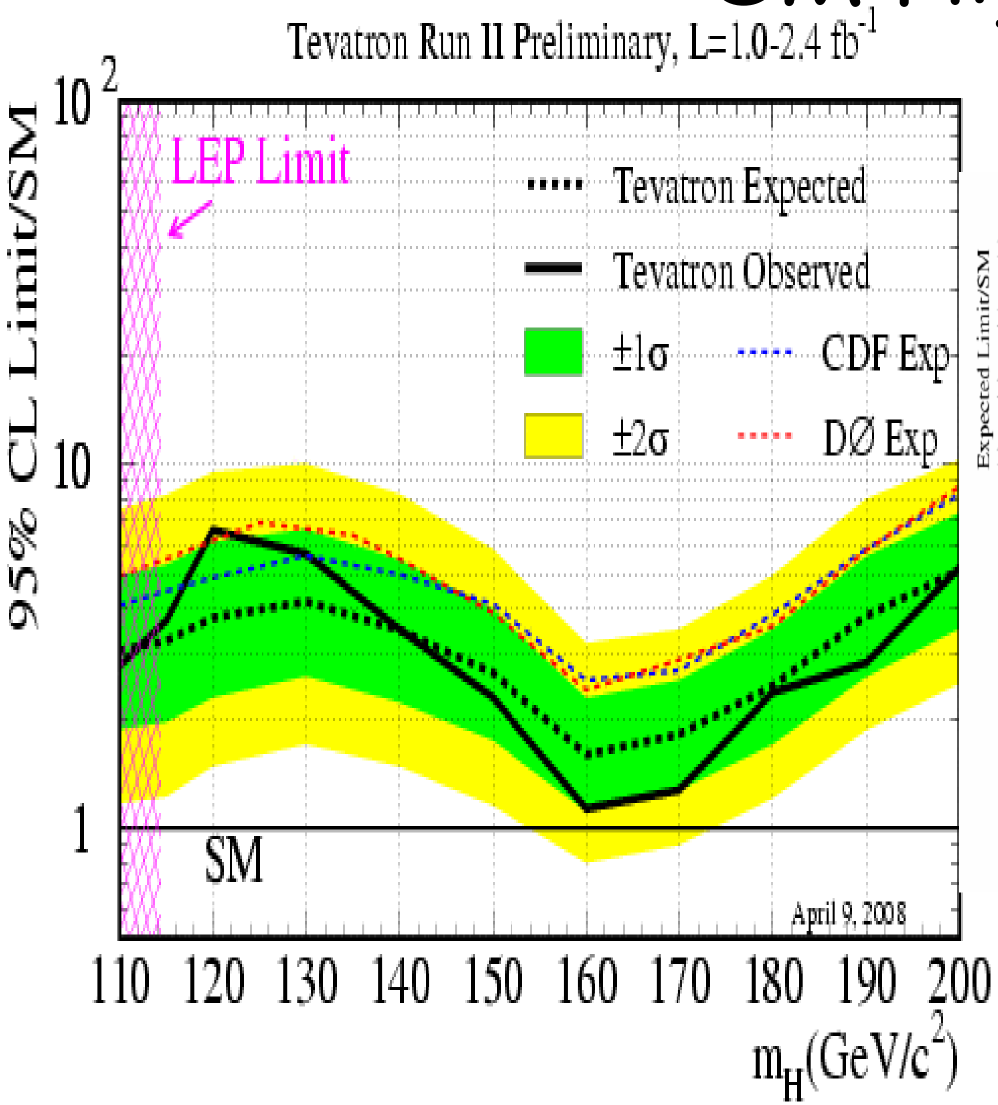




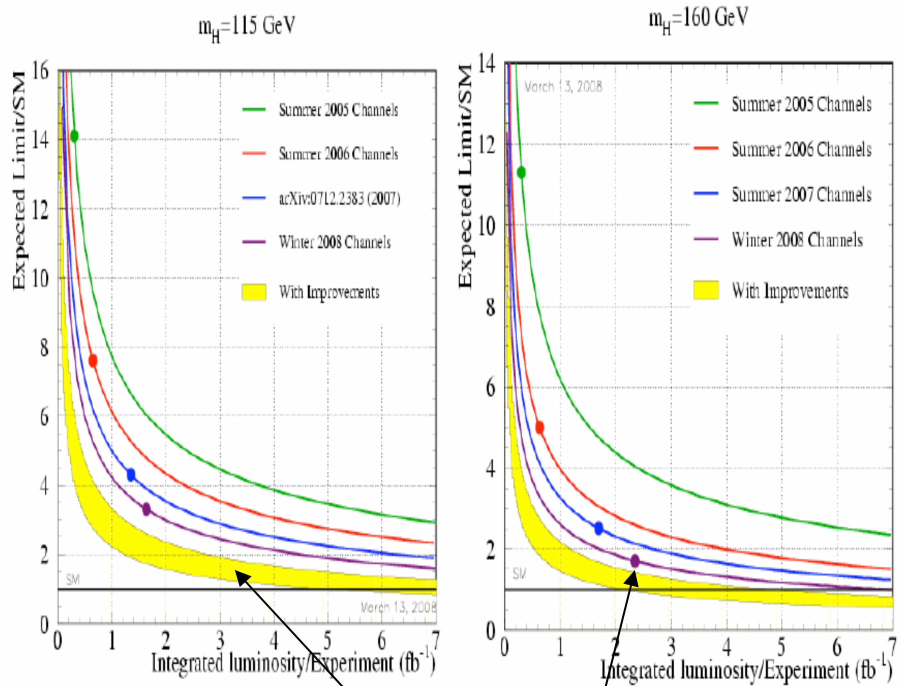
gg->H channel indistinctive signature from QCD for low Higgs mass (bb decay) but very promising for heavy higgs → WW

For low mass W/Z + H channel considered

SM Higgs



Projections vs Int. Lumi



Improvements required in b-tagging efficiency, dijet mass resolution…

Lepton coverage (electron/muons) already increased in Diboson analyses

Tevatron has a real chance to exclude Higgs masses around 160 GeV/c2 already this year

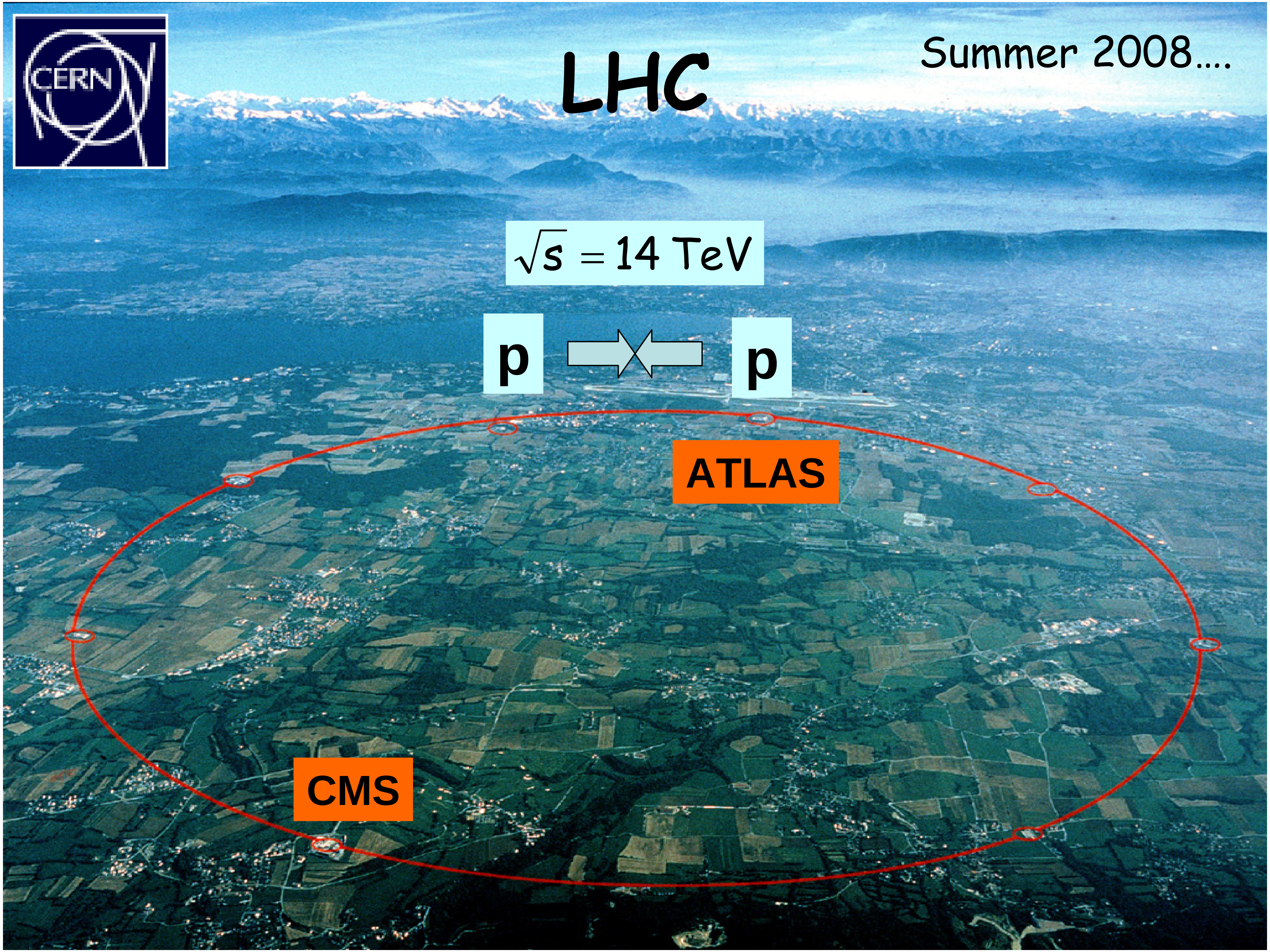
Well….

No significant excess compared to SM …yet

Tevatron will deliver a total of 6-7 fb-1 by the end of FY2009

..we will be able to start excluding some Higgs mass regions (W^+W^- channel)

…making LHC colleagues rather nervous …

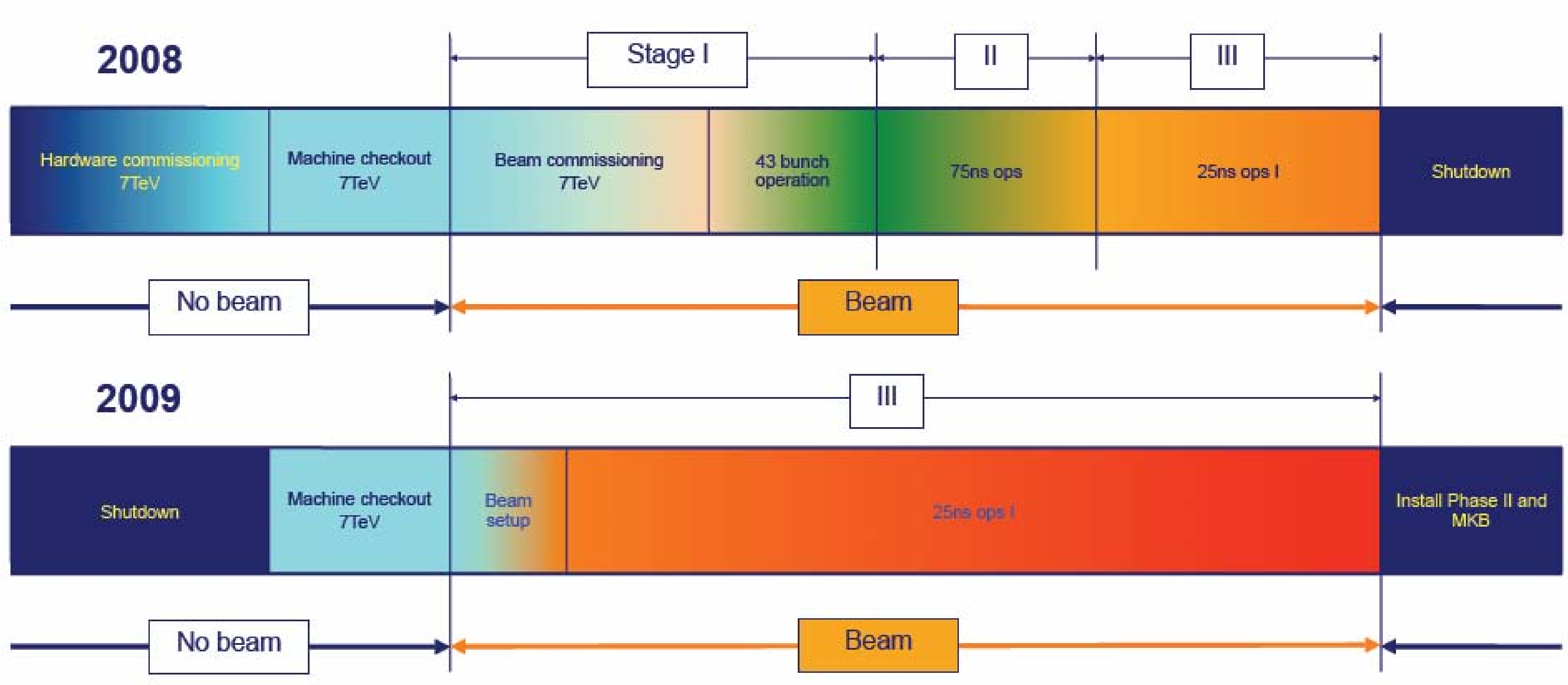

LHC
Summer 2008....
$\sqrt{s} = 14$ TeV
p
p
ATLAS
CMS

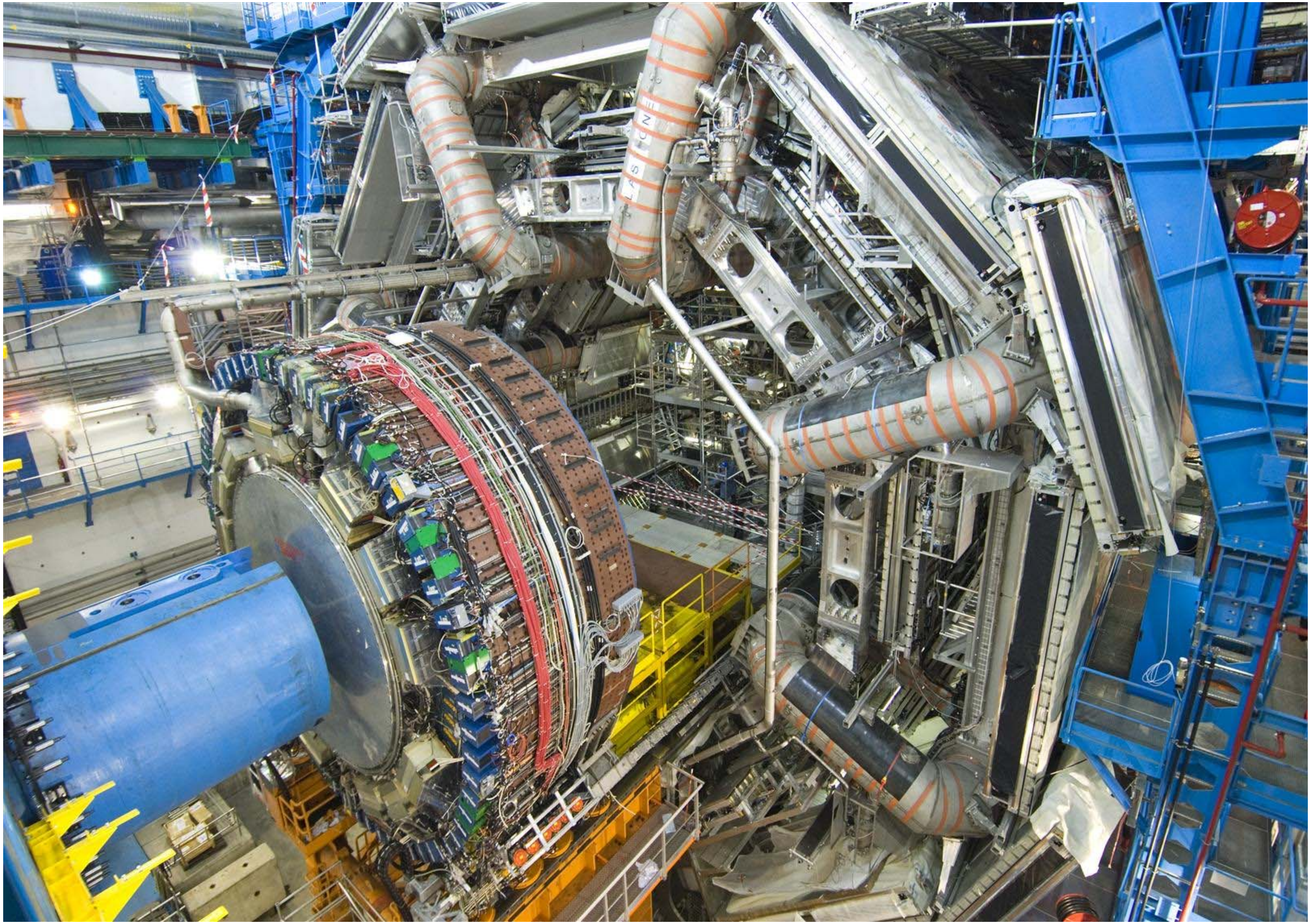
LHC Schedule

- End of May 2008: machine closed
- End of June 2008: beam commissioning at 7 TeV (now 5 TeV)

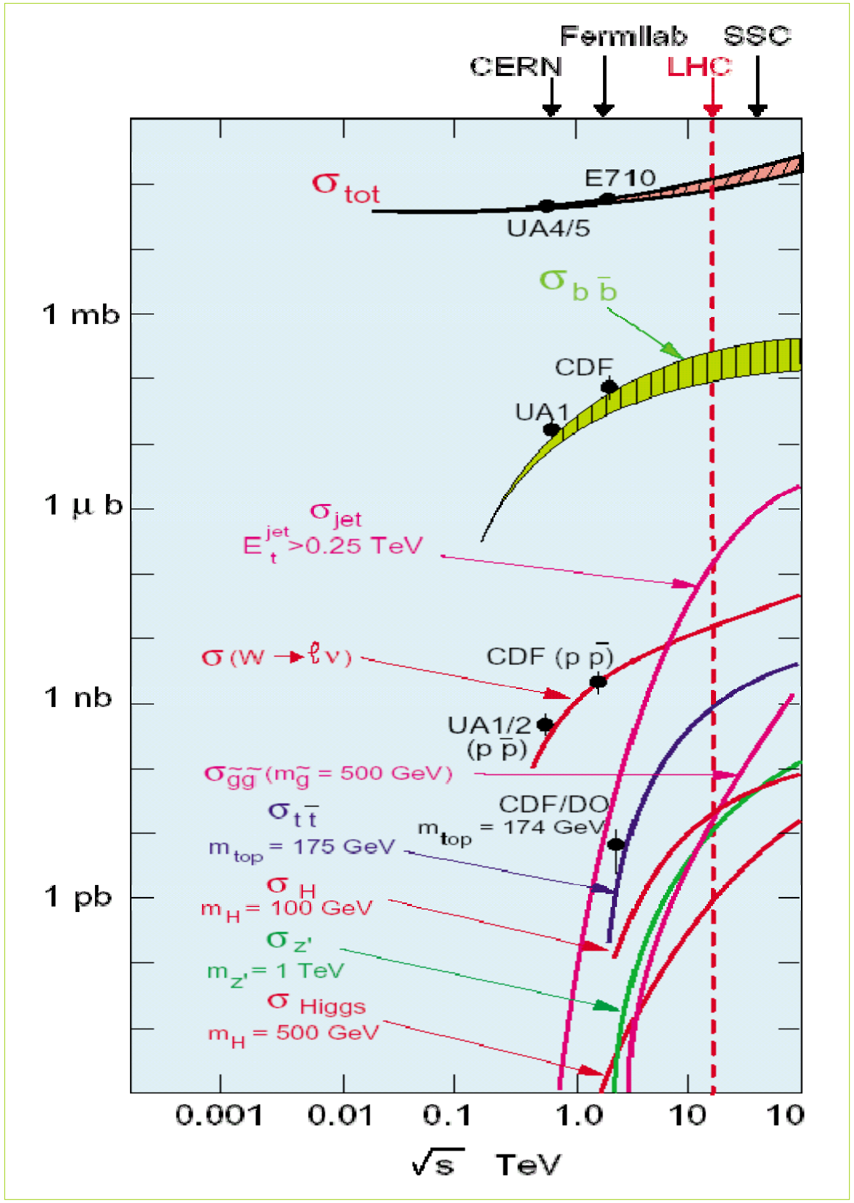
→ **1-2 months for colliding beams at 14 TeV (now at 10 TeV)**

→ **10^{32} $cm^{-2}s^{-1}$ by end 2008 (~100 pb^{-1} int. luminosity)**





Cross Sections

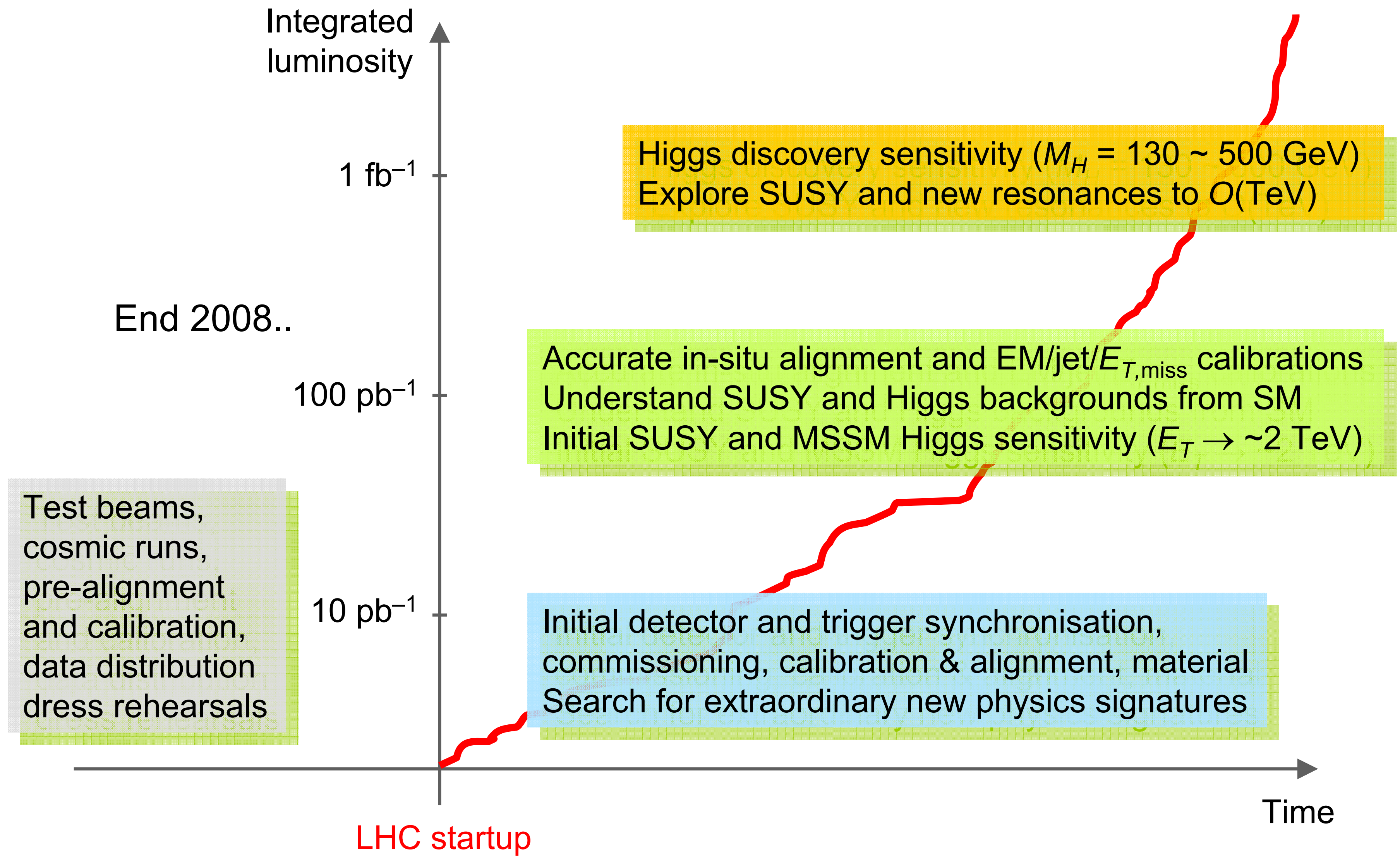


Process	σ (nb)	Events ($\int \mathcal{L} dt$ = 100 pb^{-1})
Min bias	10^8	$\sim 10^{13}$
$b\bar{b}$	$5 \cdot 10^5$	$\sim 10^{12}$
Inclusive jets $p_T > 200$ GeV	100	$\sim 10^7$
$W \to e\nu, \mu\nu$	15	$\sim 10^6$
$Z \to ee, \mu\mu$	1.5	$\sim 10^5$
$t\bar{t}$	0.8	$\sim 10^4$

Illustrative trigger menu at $\mathcal{L} = 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (ATLAS):

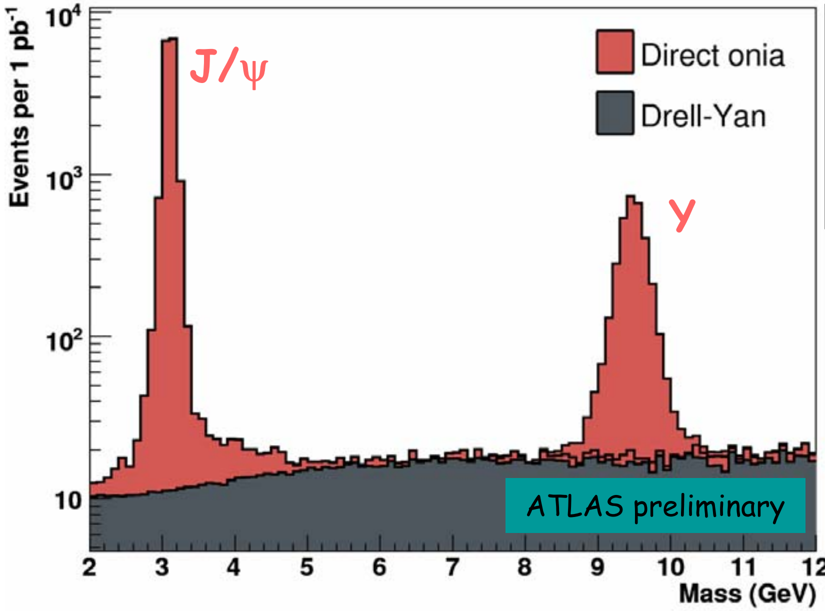
Signature	Examples of physics coverage		Rates(Hz)
minimum bias	Prescaled trigger item		10
e10,2e5	b,c$\to$e,W,Z,Drell-Yan,tt,J/ψ,Υ	electrons	$\sim$27
γ20,2γ15	Direct photon, photon pairs, γ-jet balance	photons	$\sim$7
μ10,2μ4	b,W,Z,Drell-Yan,tt,J/ψ,Υ	muons	$\sim$22
j120,4j23	QCD,high p_T and multi-jet final states	jets	$\sim$13
τ20i+$^{e10}_{\mu 6}$	Z$\to\tau\tau$	taus	4
τ20i+xE30	W,tt	tau+$\not{E}_T$	$\sim$10
	Prescaled,calibration,monitoring triggers		$\sim$17
Total HLT rate			$\sim$100

Start-up Programme in a Nutshell



The first peaks …

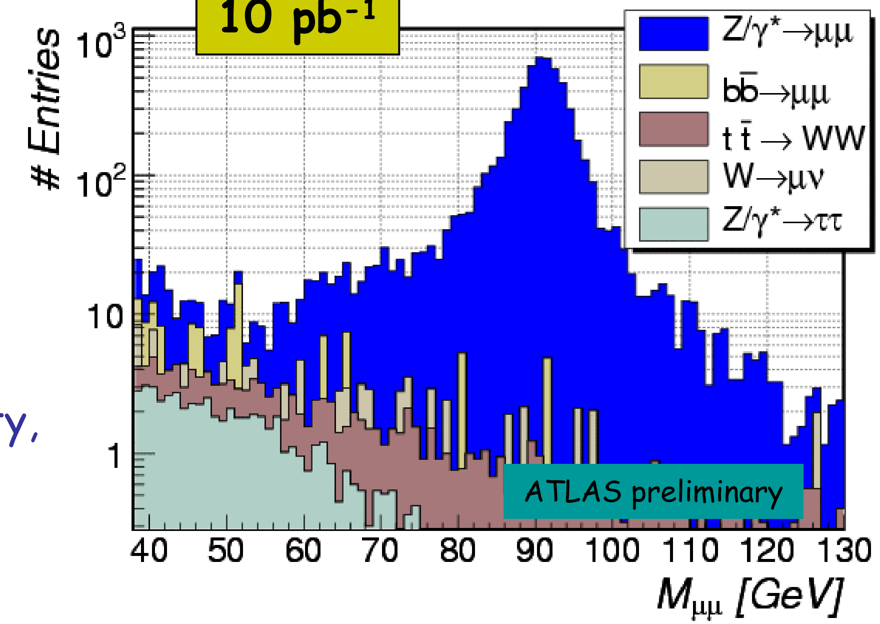
1 pb^{-1}≡3 days at 10^{31} at 30% efficiency



After all cuts:
~ 4200 (800) J/ψ (ϒ) → μμ evts per day at L = 10^{31}
(for 30% machine x detector data taking efficiency)
~ 15600 (3100) events per pb^{-1}

→ tracker momentum scale, trigger performance, detector efficiency, sanity checks, …

10 pb^{-1}

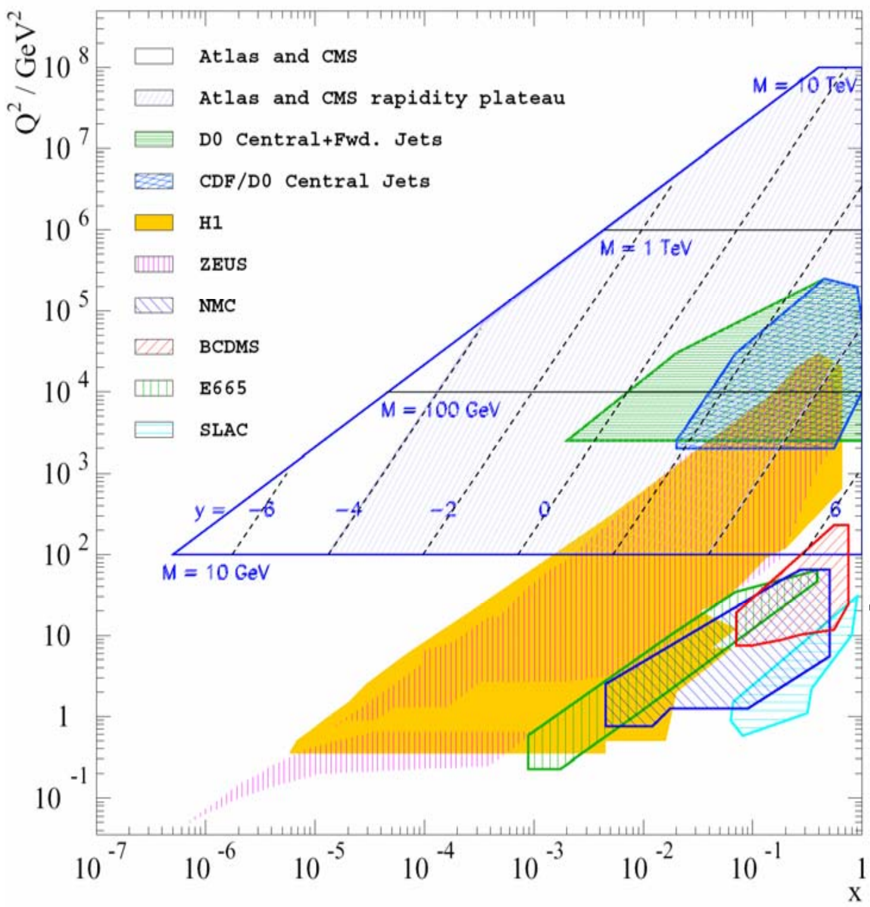


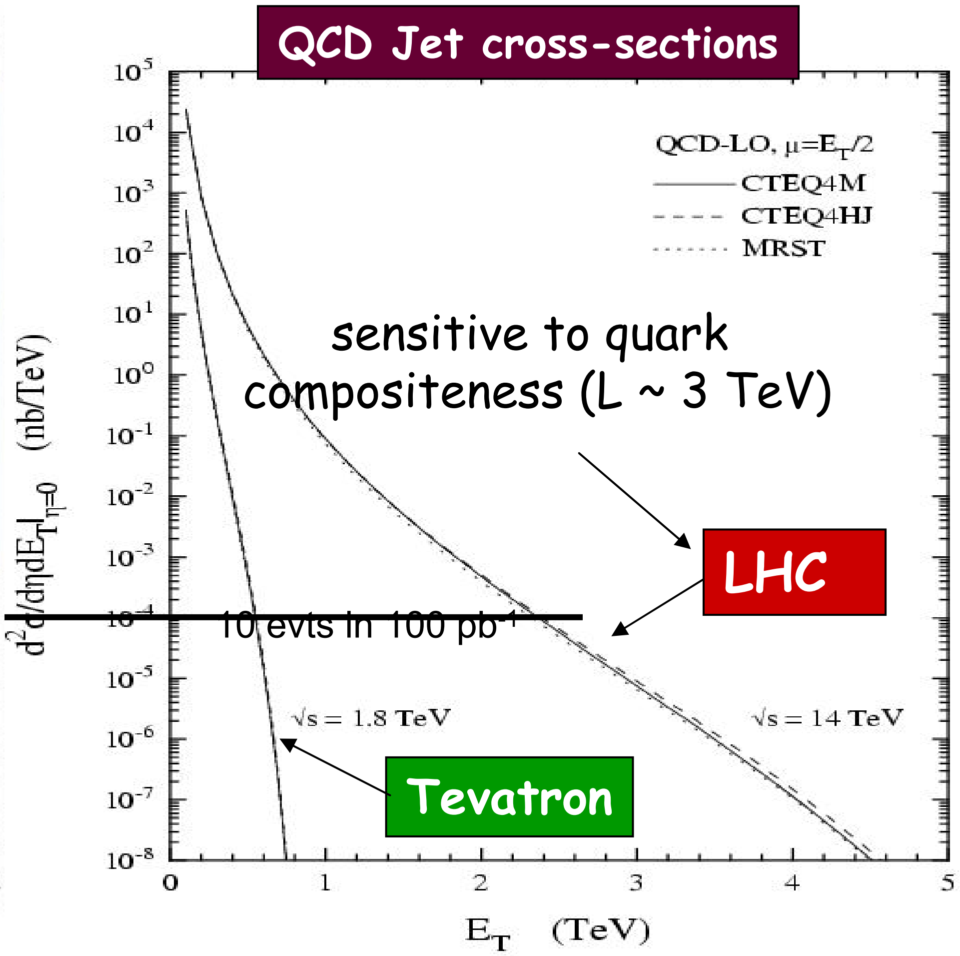
After all cuts:
~ 160 Z → μμ evts per day at L = 10^{31}
~ 600 events per pb^{-1}

→ Muon Spectrometer alignment, ECAL uniformity, energy/momentum scale of full detector, lepton trigger and reconstruction efficiency, …

Precision on σ (Z→μμ) with 100 pb^{-1}: <2% (experimental error), ~10% (luminosity)

Jets

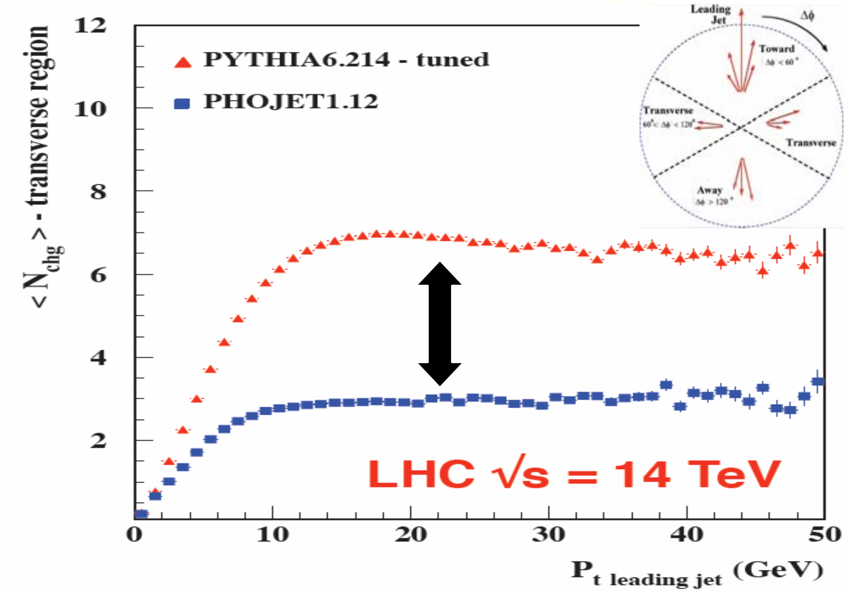


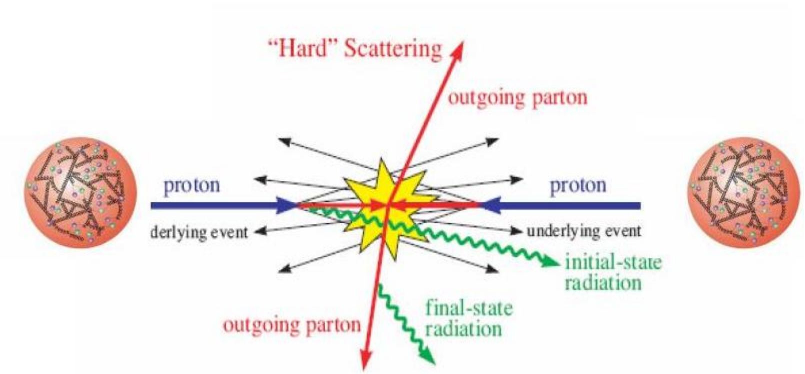


It is clear that LHC will explore 2-3 TeV jets rather soon…

(~5-10% (?) uncertainty on jet energy scale expected on day 1…lots of work ahead of us)

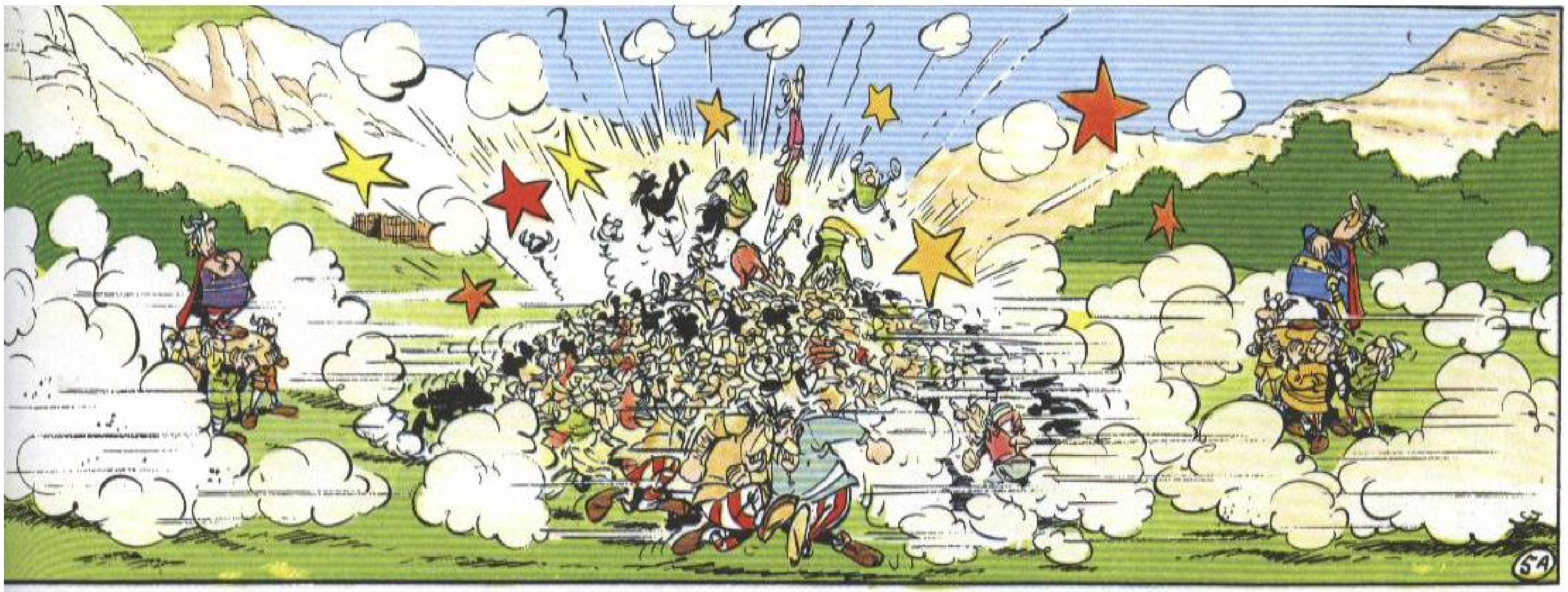
Notes on Underlying Event



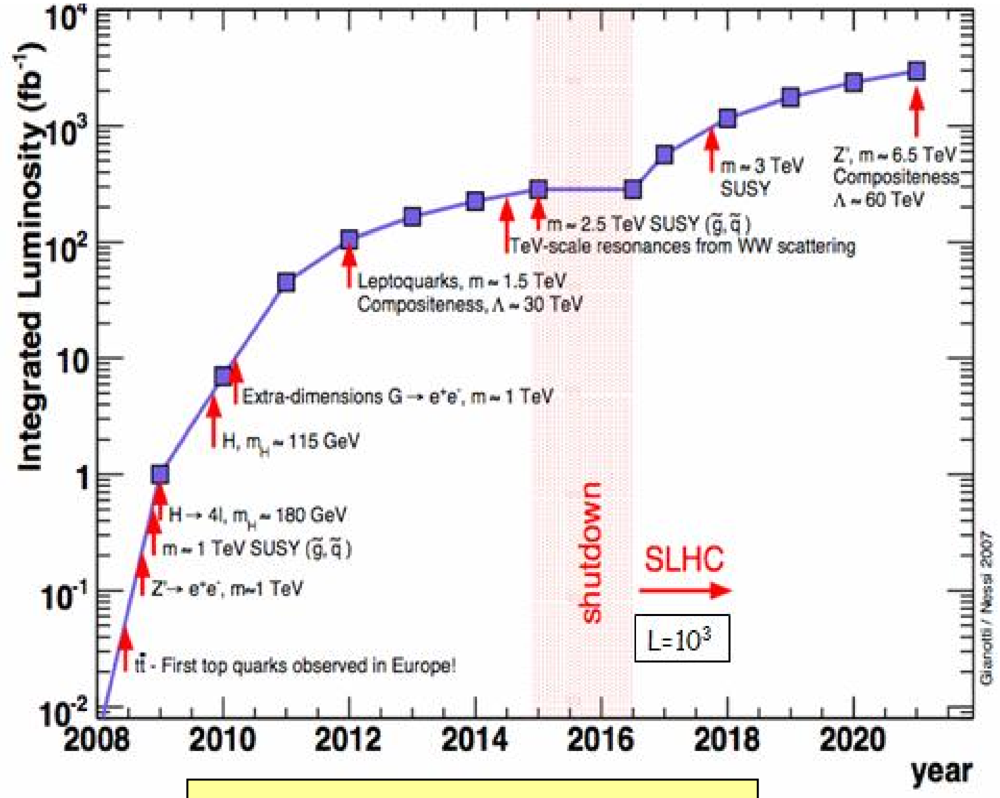


This is a clear unknown at LHC energies

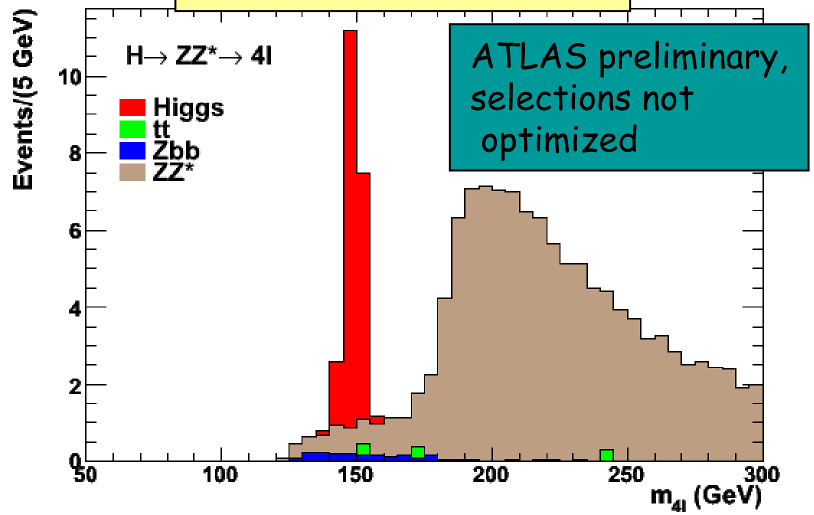
- Dependence with physics process
- How "hard" will be ?



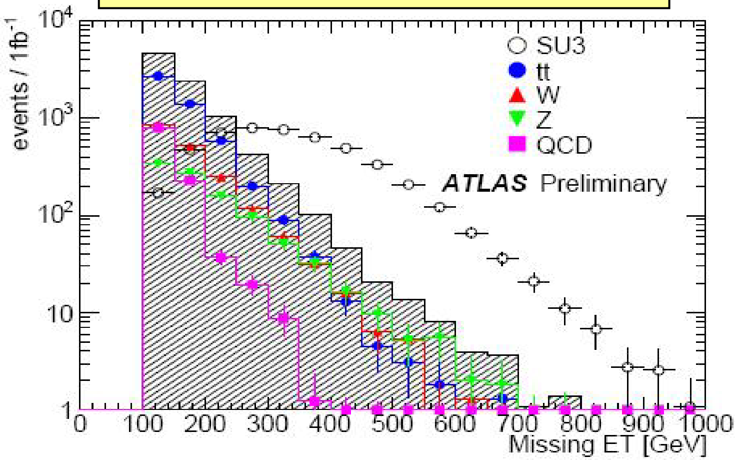
Physics vs Time/Lumi



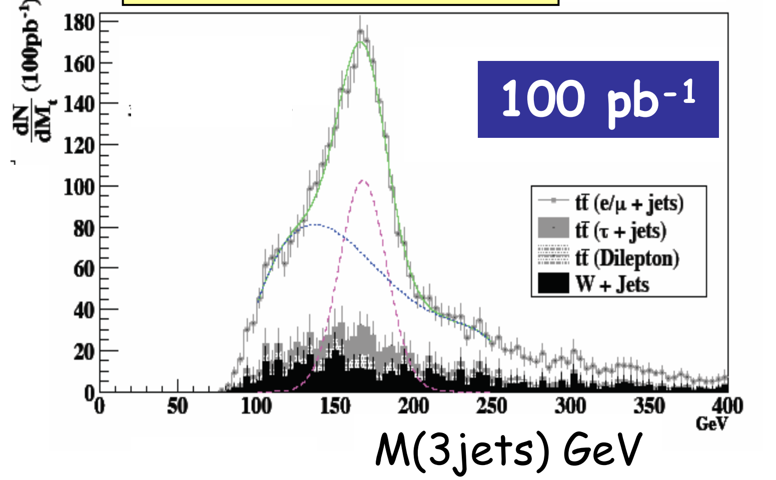
H → ZZ* → 4l, 10 fb^{-1}



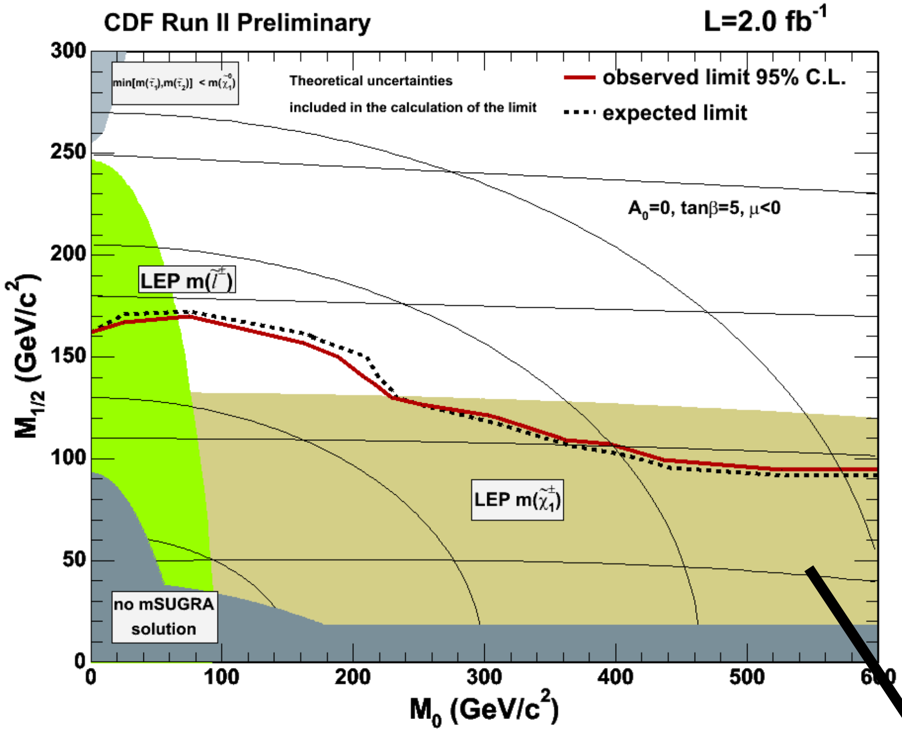
Squark/Gluinos 100 pb^{-1}

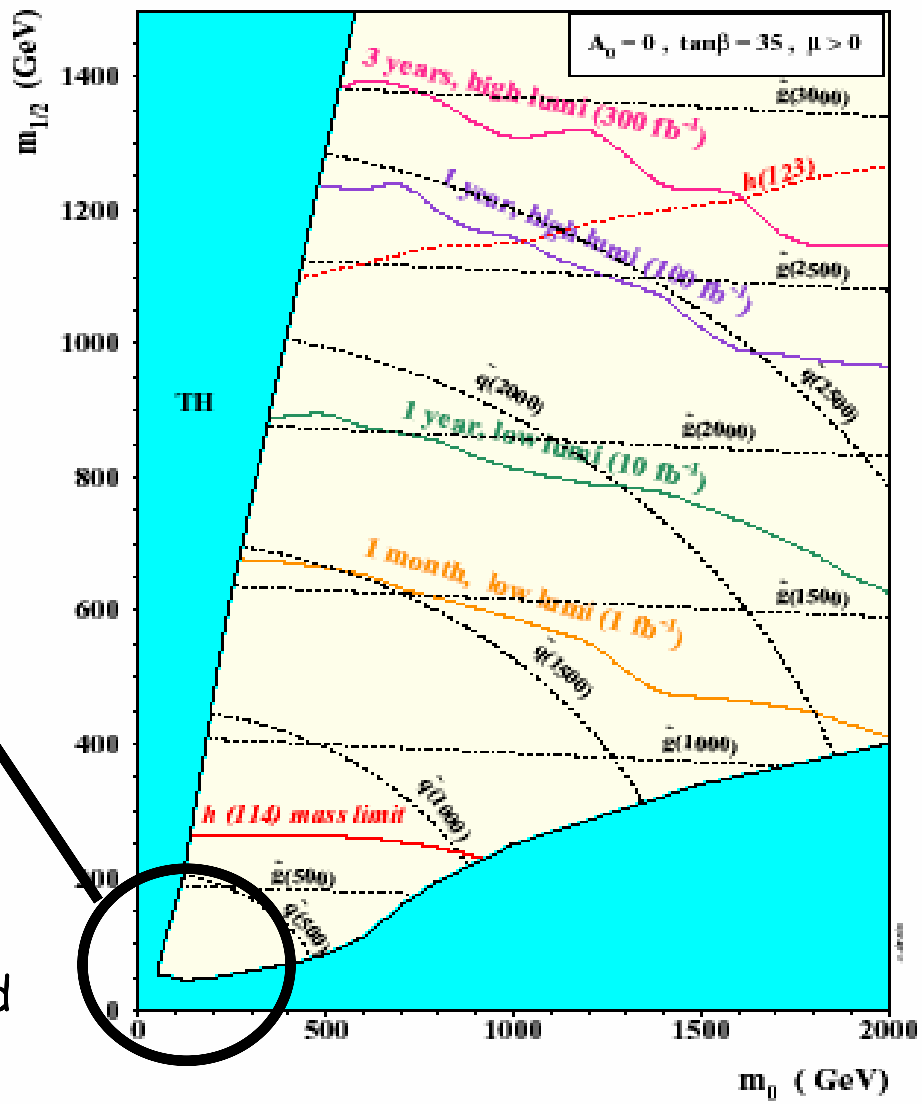


Top (no b-tagging)



SUSY Searches at the LHC

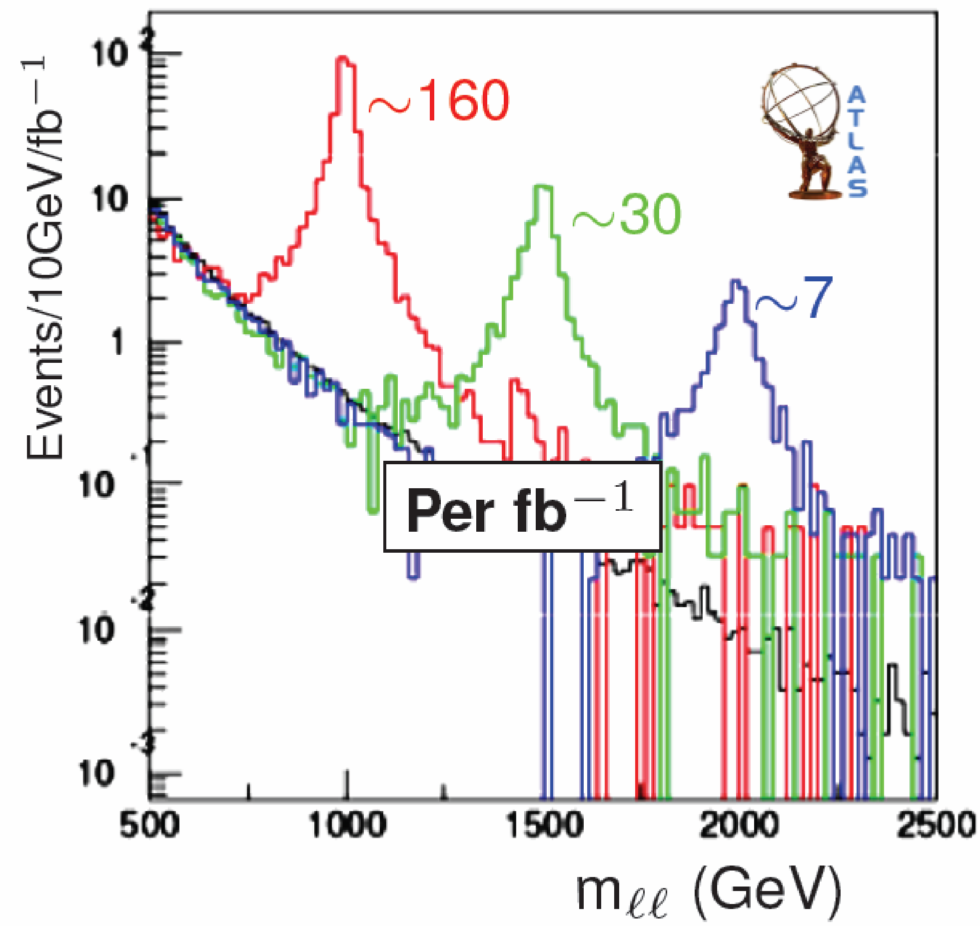




The LHC is built to discover SUSY
If there, we will find it relatively soon

But…we do not underestimate the commissioning phase and the work needed to understand the SM backgrounds (QCD-jets, top, Boson+jets….)

My Dream ($X' \rightarrow e^+e^-$)



Mass (TeV)	$\int \mathcal{L}dt$ for discovery
1	**$\sim$70 pb^{-1}**
1.5	$\sim$300 pb^{-1}
2	$\sim$1.5 fb^{-1}

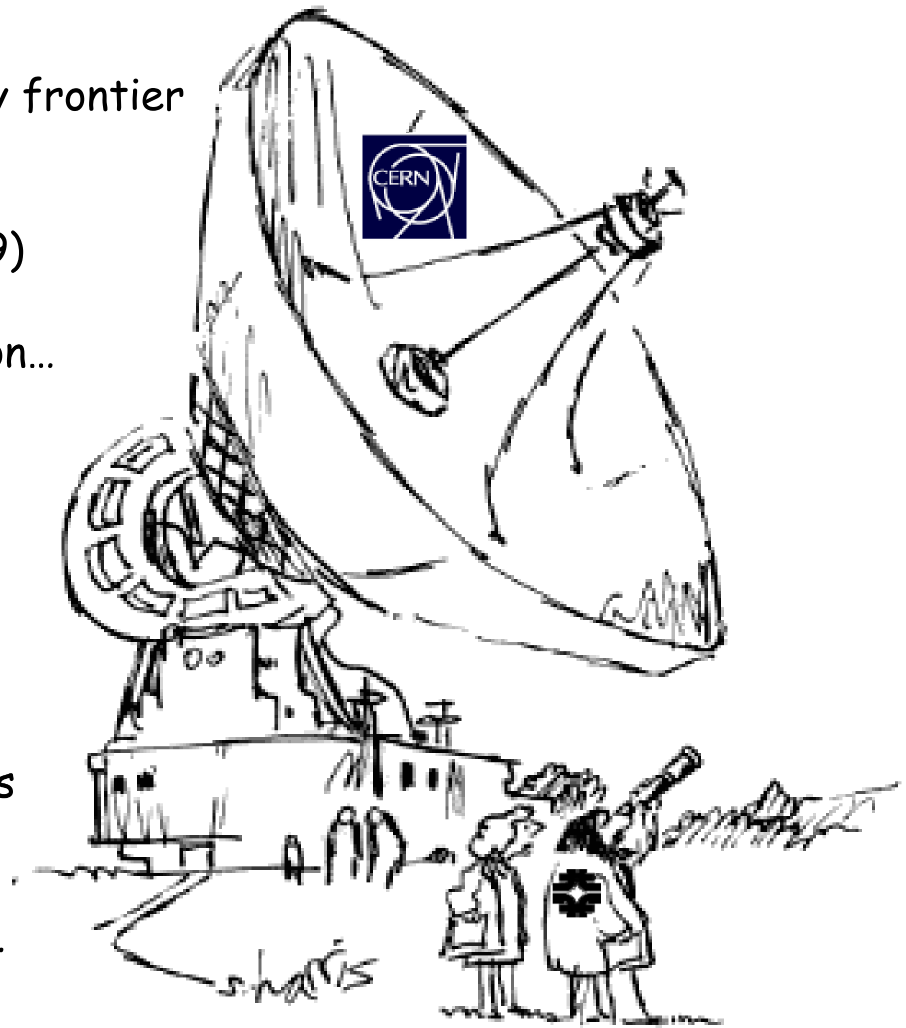
please !!!!

...or at least that we would not need a real princess to find the pea.. (under the SM background)

Final Random Notes on the Future

- Since 2001 Tevatron experiments carry out consistent physics programs with great success...the only ones in town at the Energy frontier
    - Expect ICHEP08 results with 3 fb-1 (a total of 6-7 fb-1 on tape by end 2009)
- Tevatron FY2010 running is under discussion…
- Both CDF and D0 collaborators now deeply involved in ATLAS/CMS …while aiming to complete their Tevatron program
    - Window of Opportunity to SM Higgs
    - Well understood detectors/datasets
    - Still we could find a hit of New Physics
- LHC starts operations this summer but a long commissioning phase ahead of us… (delicate transition phase for all groups)

→We all hope 2009 will bring the desired breakthrough in Particle Physics…



"Just checking."