Particle Physics Phenomenology and the LHC

Introductory lectures on
what we are going to look for at the LHC, why and how.

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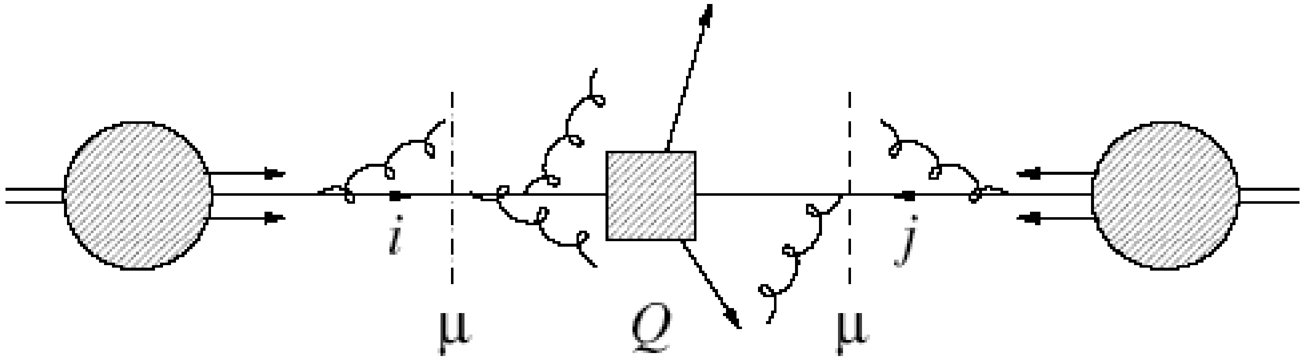
Outline

$SU(3)_C \times SU(2)_L \times U(1)_Y$

- Introduction
- QCD in hadron collisions
- EW symmetry and its breaking in the SM
- SM and BSM phenomenology at the LHC

Remember on our master formula



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}\left(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2}\right)$$

PDF's

short-distance x-sec

- By calculating the short distance coefficient at tree-level we obtain the first estimate of rates for inclusive final states.

- A cross section at LO can strongly depend on the factorization and renormalization scales. Improvement on the scale dependences are obtained by going higher orders in the perturbative expansion for the short distance coefficient

$$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

and the evolution equations for the PDFs.

- Today calculations at tree-level and at NLO for a final state F with a few partons can be evolved and unfolded by a parton shower MC to produce a fully exclusive description of an event.

PDF's

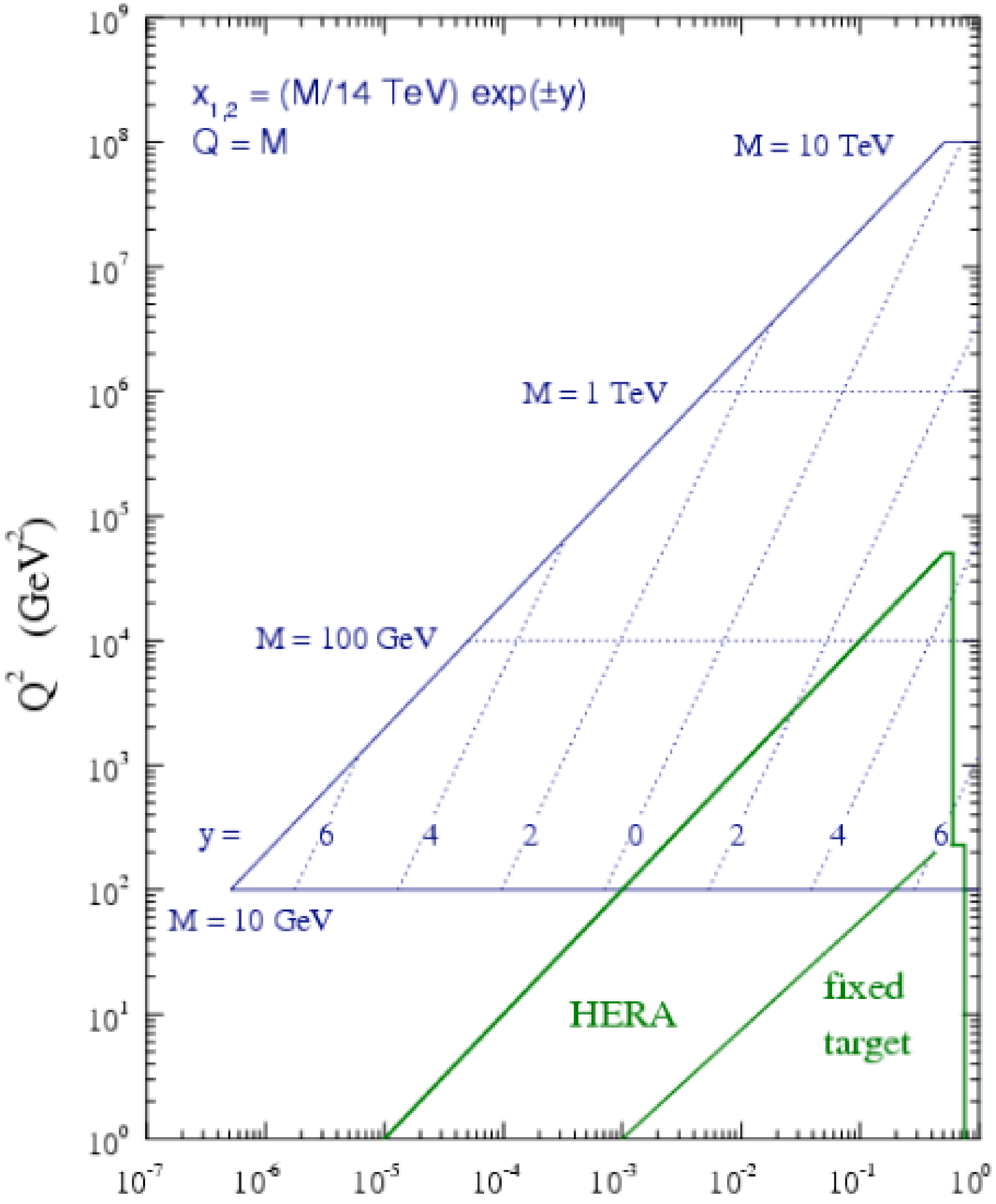
PDF measured at HERA and fixed-target experiments. x dependence from data.
Q^2 dependence from DGLAP evolution.

Status:

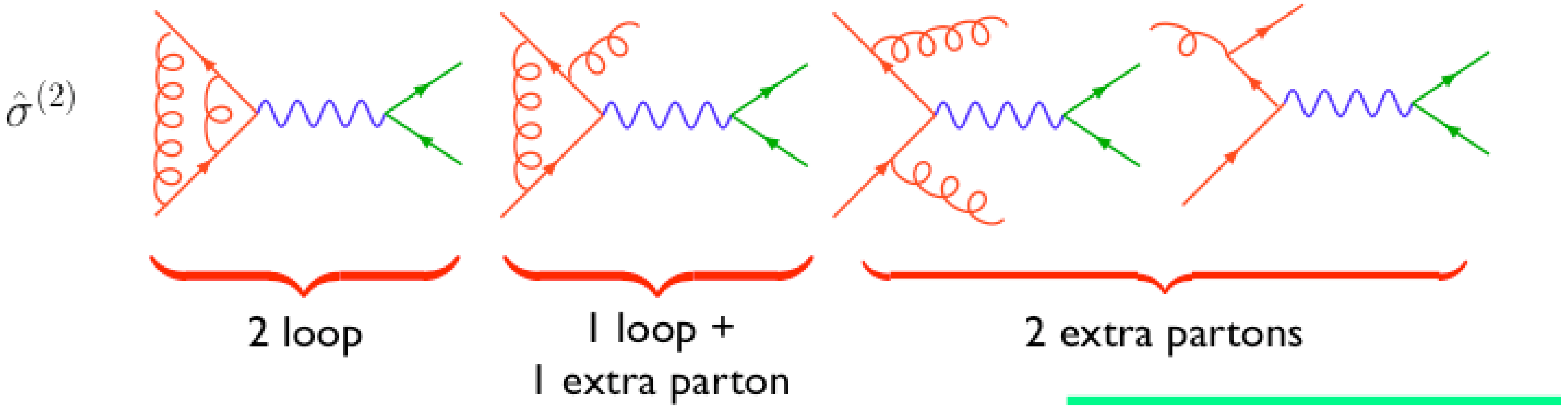
NNLO calculation of the 3-loop splitting kernels ("the hardest calculation in QCD") [Moch,Vermaseren,Vogt. 2004]

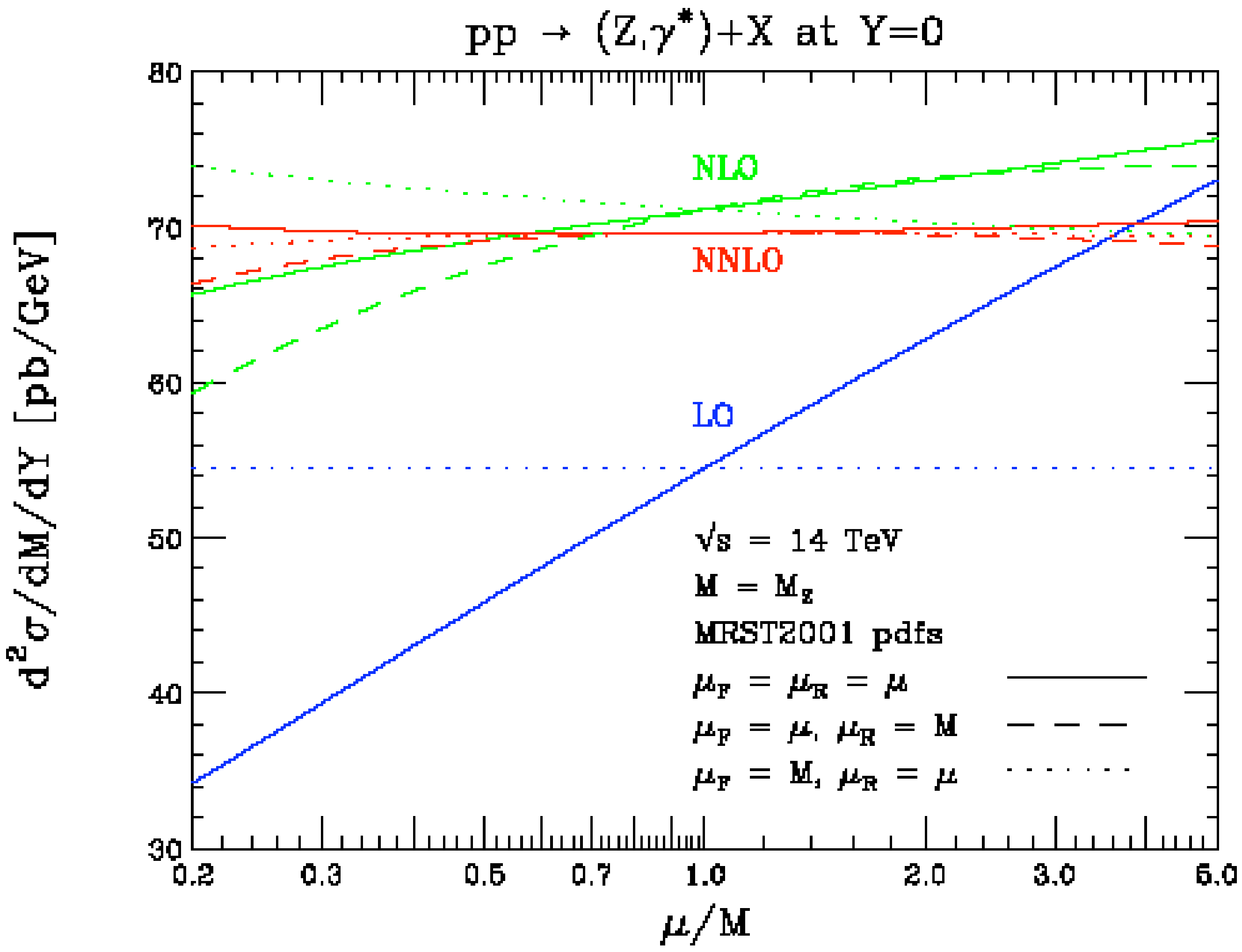
Together with short distance NNLO calculation first sets of NNLO PDF sets. [MRST and Alekhin, 2004]

PDF's with errors: Various "traditional methods",[CTEQ and MRST, 2003]. Also new approaches, the functional space [Giele, Keller, Kosower.2001] and the Neural Network approach [Del Debbio et al., 2008].



Improving on $\hat{\sigma}$



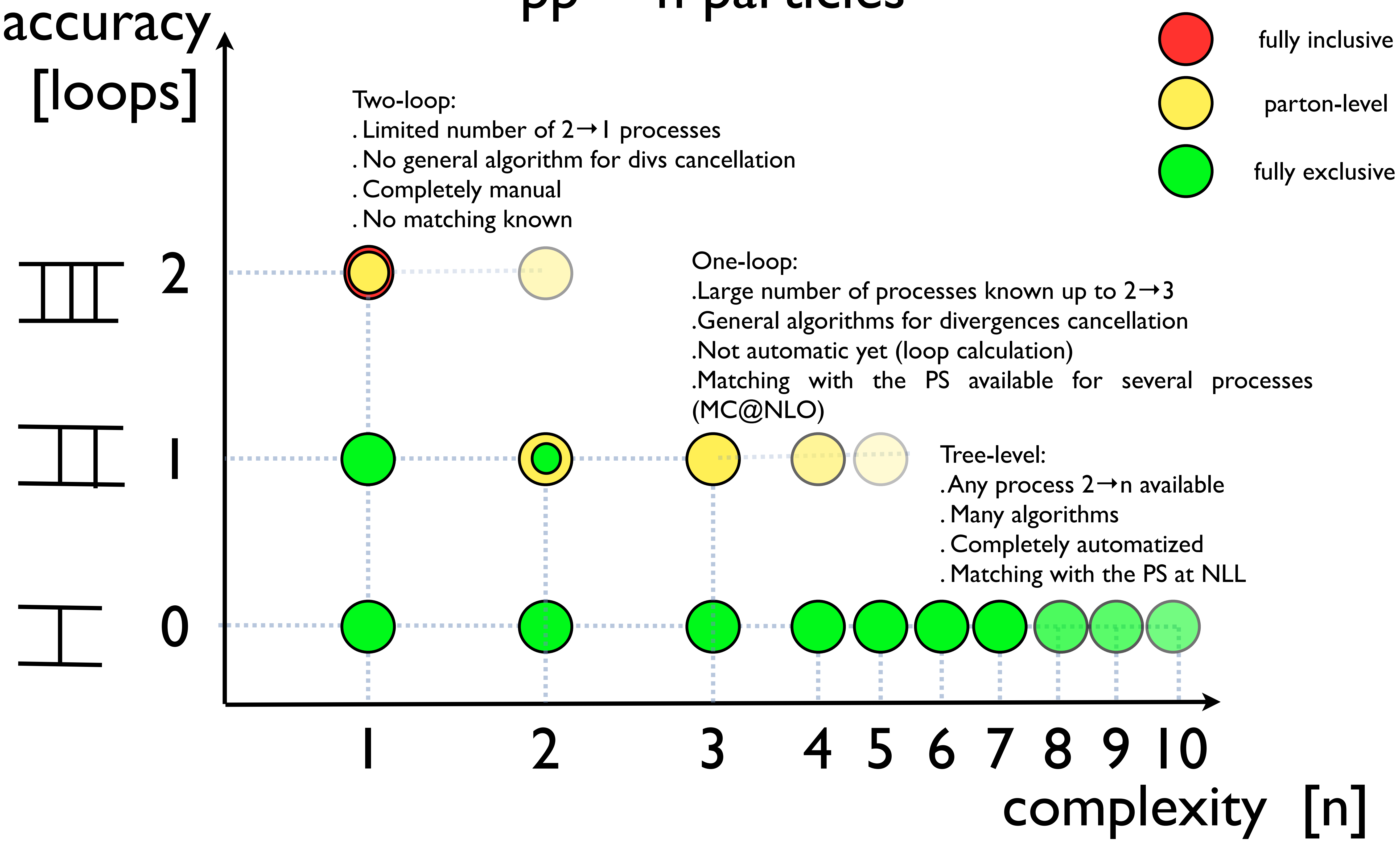


- Precision predictions at NNLO
- Also miss qualitative effects at lower orders
  - Few initial channels open; sensitivity to pdfs underestimated
  - Few jets in final state
  - Jets modeled by too few partons
  - Incorrect kinematics, e.g., no p_T

[Anastasiou, Dixon, Melnikov, Petriello. 2004]

Status

pp→ n particles



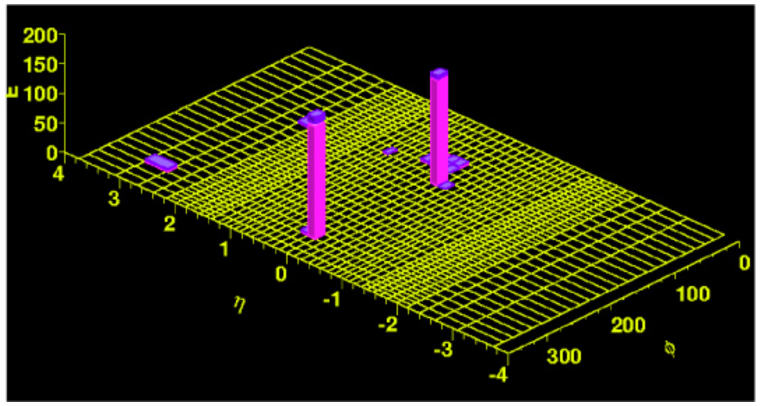
Two-loop:
. Limited number of 2→1 processes
. No general algorithm for divs cancellation
. Completely manual
. No matching known

One-loop:
.Large number of processes known up to 2→3
.General algorithms for divergences cancellation
.Not automatic yet (loop calculation)
.Matching with the PS available for several processes (MC@NLO)

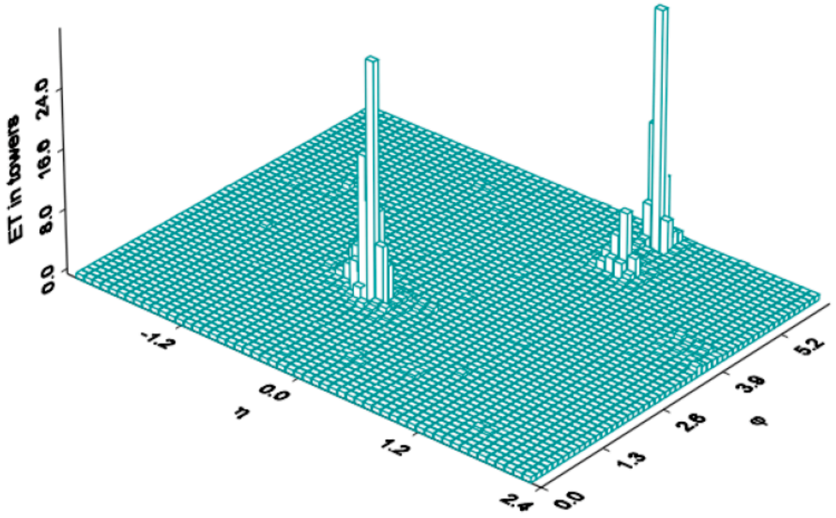
Tree-level:
.Any process 2→n available
. Many algorithms
. Completely automatized
. Matching with the PS at NLL

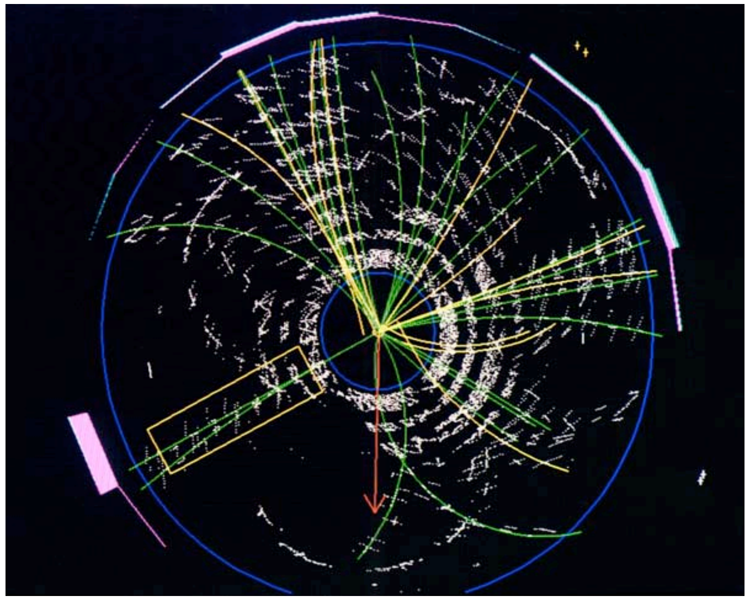
SM pheno

Drell-Yan

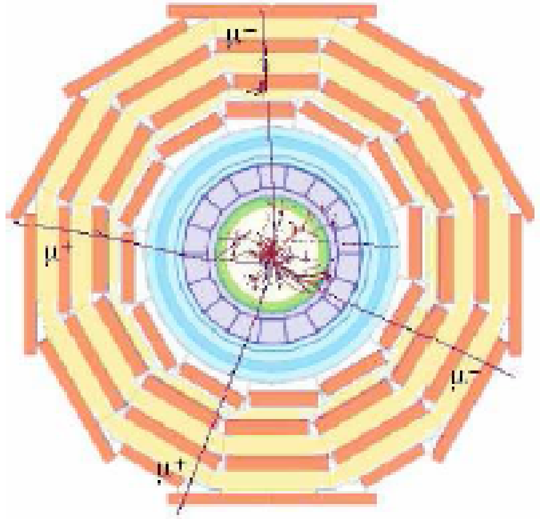


Jets



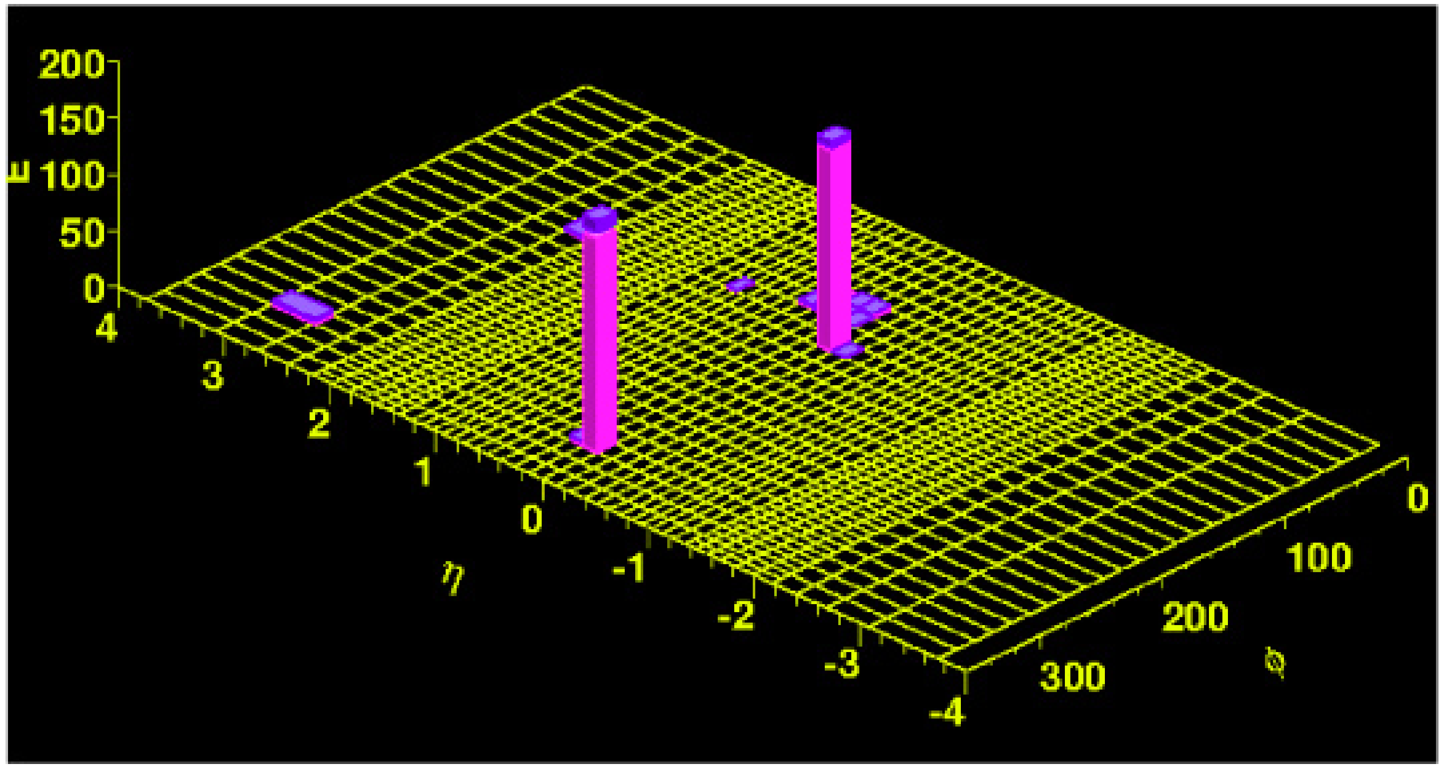


Top

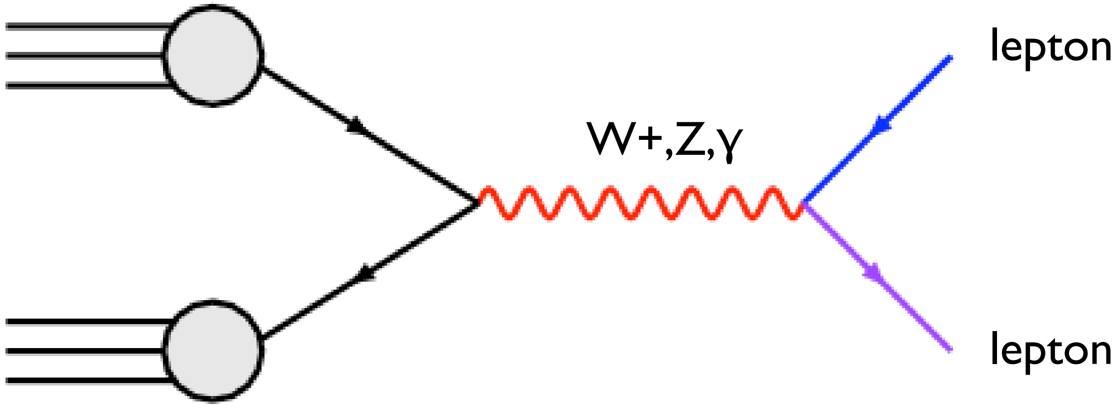


Higgs

Drell-Yan



Drell-Yan

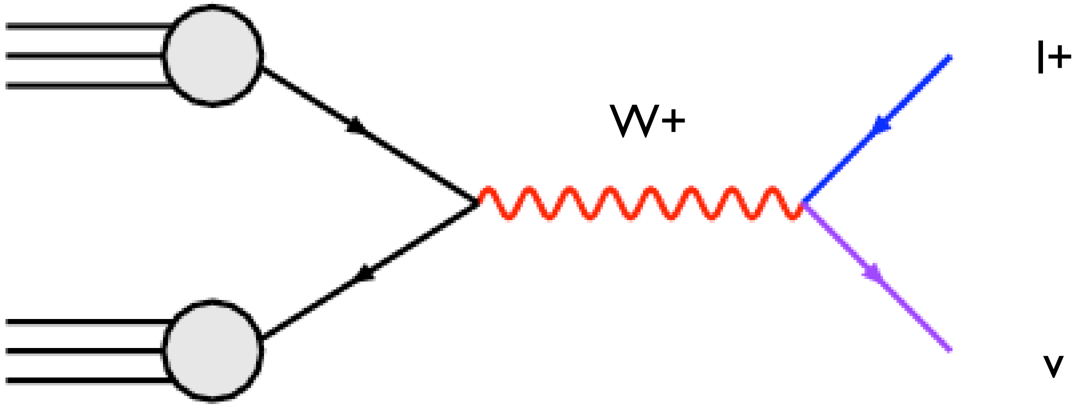


- Clean final state (no hadrons from the hard process).
- Nice test of QCD and EW interactions. The cross sections are known up to NNLO (QCD) and at NLO (EW).
- Measure m_W to be used in the EW fits together with the top mass to guess the Higgs mass.
- Constraint the PDF
- Channeel to search for new heavy gauge bosons or new kind of interactions

W cross section

$$\sigma^{th}(W) = \sum_{ab} \mathcal{P}_{ab} \otimes \hat{\sigma}_{ab}(W)$$

$$\sigma^{exp}(W) = \frac{1}{BR(W \to \ell\nu)} \frac{1}{\int \mathcal{L} dt} \frac{N^{sig}}{A_W}$$



For measuring σ(W), one needs to estimate the acceptance A_W from theory and the luminosity from an independent source. A fully exclusive description of the final state is needed.

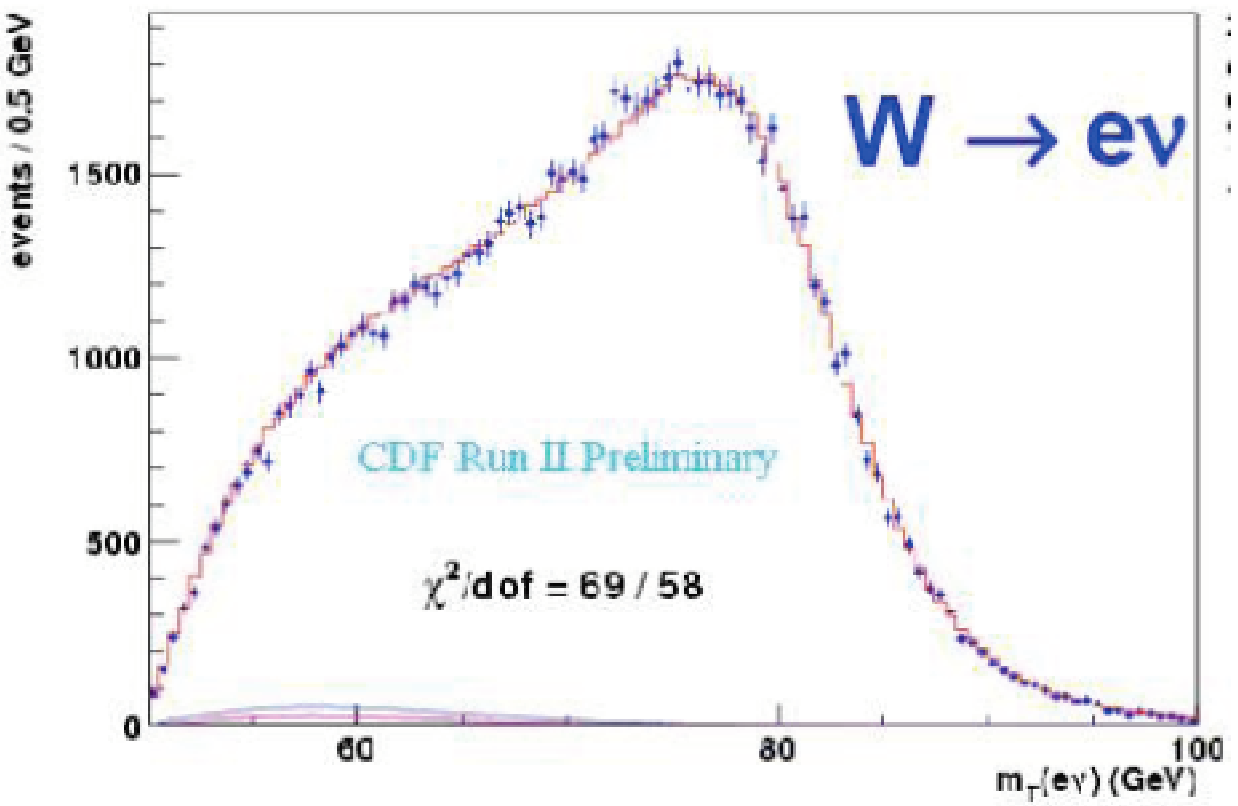
If theory is accurate enough, one can use σ(W) to:

0. Indirectly measure Γ_W
   (from R= σ(W) BR(W→lν)/σ(Z) BR(Z→ll))
1. Extract direct information on the PDF
2. Measure the collider luminosity
3. Extract parton-parton luminosity (=luminosity+PDF)
   ⇒ Use W and Z as standard candles!!

Theory Status:

Best QCD predictions at present:
>Exclusive NNLO calculation WITH spin correlations [Melnikov, Petriello 2006]
> Fully exclusive (PS interfaced) prediction at NLO+NLL[Frixione, Webber, 2003]
> Resummed pt distribution at NLO+NNLL [Balazs, Qiu, Yuan, 1995]
> 1-loop EW corrections [Baur, Wackeroth. 2004]

W mass

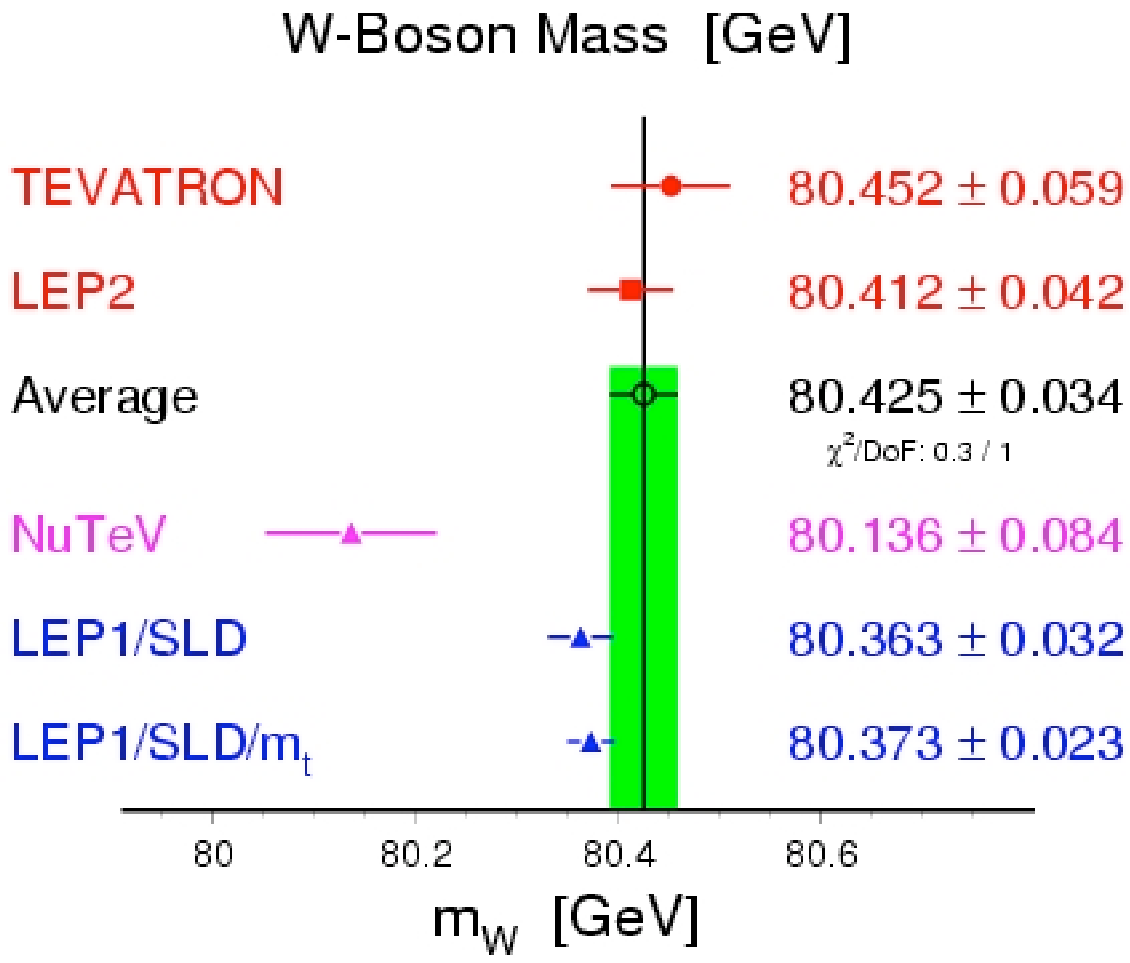


Run II expectation:

improve on LEP2 result: δm_W=40 MeV for 2fb^{-1} per lepton channel per experiment.

LHC expectation:

δm_W=15 MeV from transverse mass measurement. Might be improved (~10MeV) using the W/Z transverse mass ratio.



Need:

$$\delta m_W \sim 7 \times 10^{-3}\ \delta m_t$$

for equal contribution to m_H uncertainty.

Exercise: W rapidity asymmetries

In proton-antiproton collisions, prove that the charge rapidity asymmetry:

$$A(y) = \frac{d\sigma_{W^+}/dy - d\sigma_{W^-}/dy}{d\sigma_{W^+}/dy + d\sigma_{W^-}/dy}$$

is related to the ratio of the up and down quarks PDF ratio $R(x)=f_d(x)/f_u(x)$ via the following relation

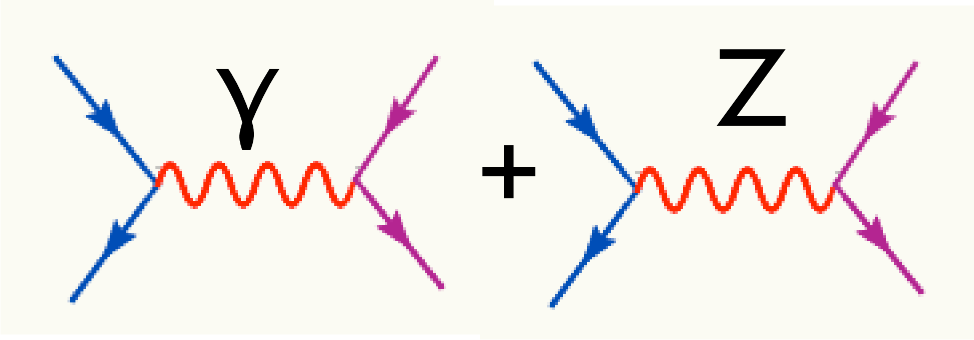
$$A(y) = \frac{R(x_2) - R(x_1)}{R(x_2) + R(x_1)} \Rightarrow A(y) \neq 0 \leftrightarrow \frac{dR(x)}{dx} \neq 0$$

W rapidity spectra would provide useful information on the x-dependence of the up and down density ratio. But the W decays to lepton neutrino. Can we use the rapidity of the lepton?

The LHC is a pp collider, so no charge asymmetry is expected.
Is there any other variable that we can come up with, that would be providing the same kind of information?

Forward-Backward asymmetry

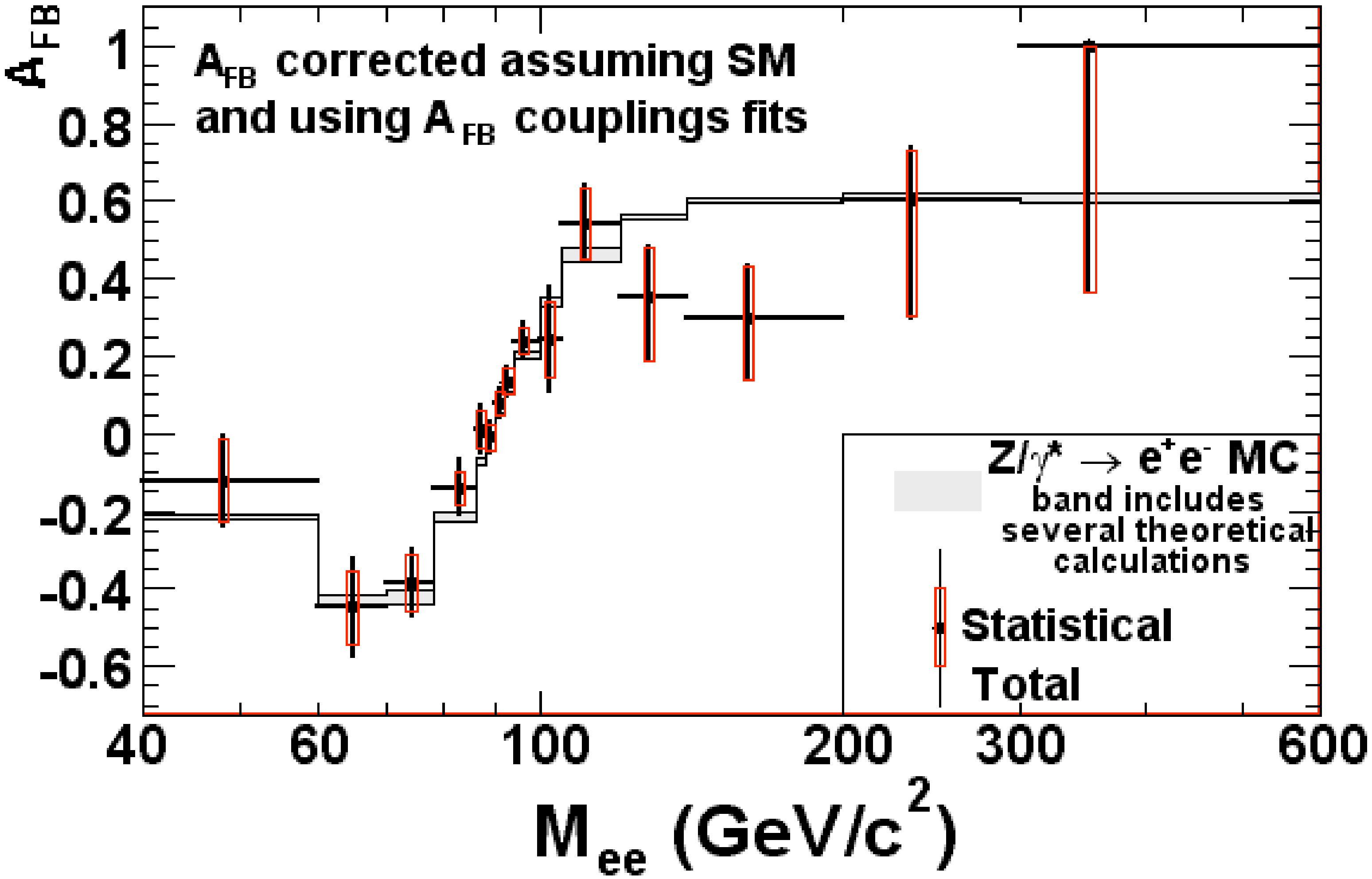
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}\frac{B}{A}$$



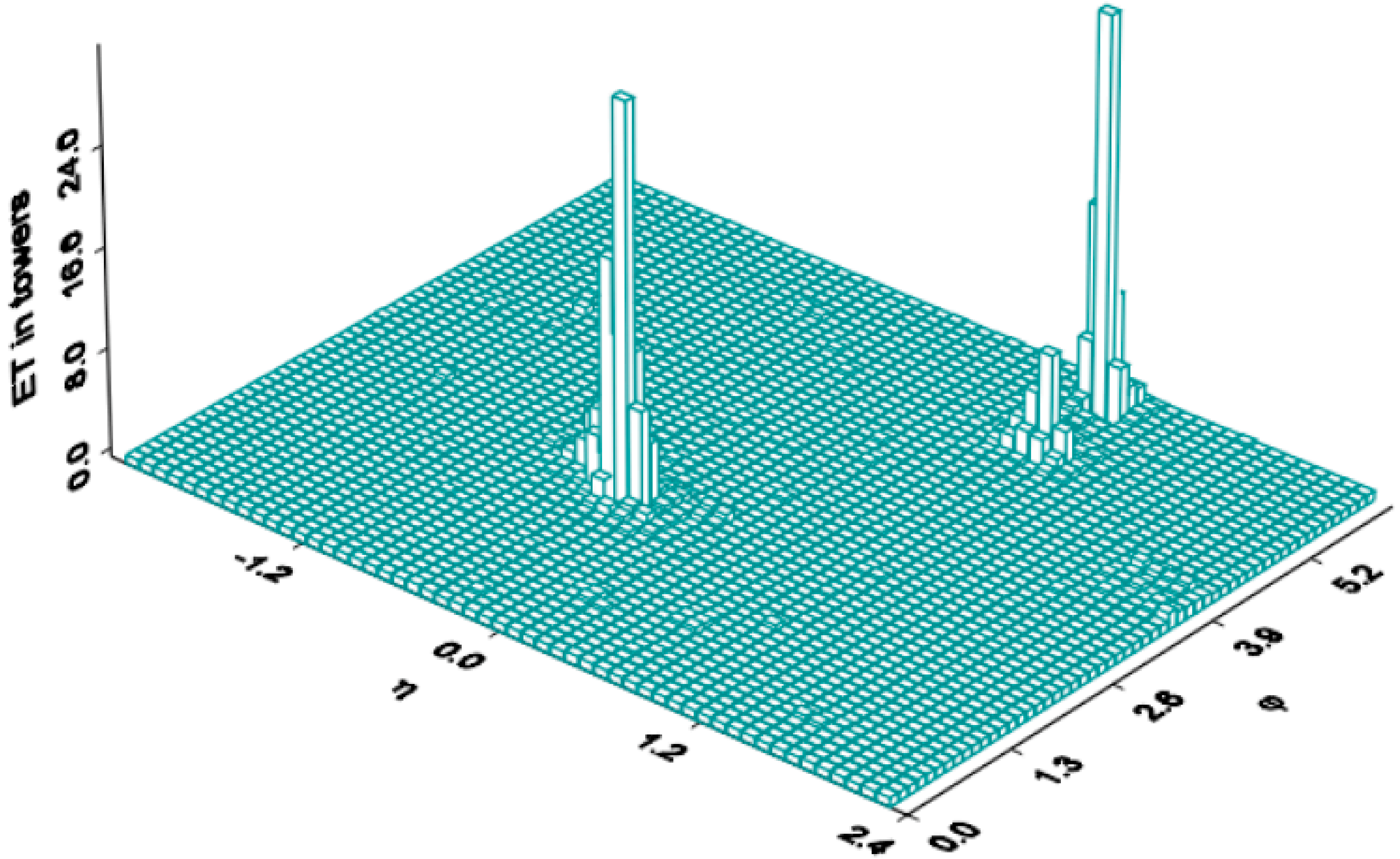
$$\frac{d\sigma}{d\cos\theta^*} = A(1+\cos^2\theta^*) + B\cos\theta^*$$

Such an asymmetry provides a very interesting check of the standard model. It is due to the γ,Z interference.

It assumes that we know which beam provided the quark and which the antiquark. At Tevatron this clear (statistically), while at the LHC will not be possible.



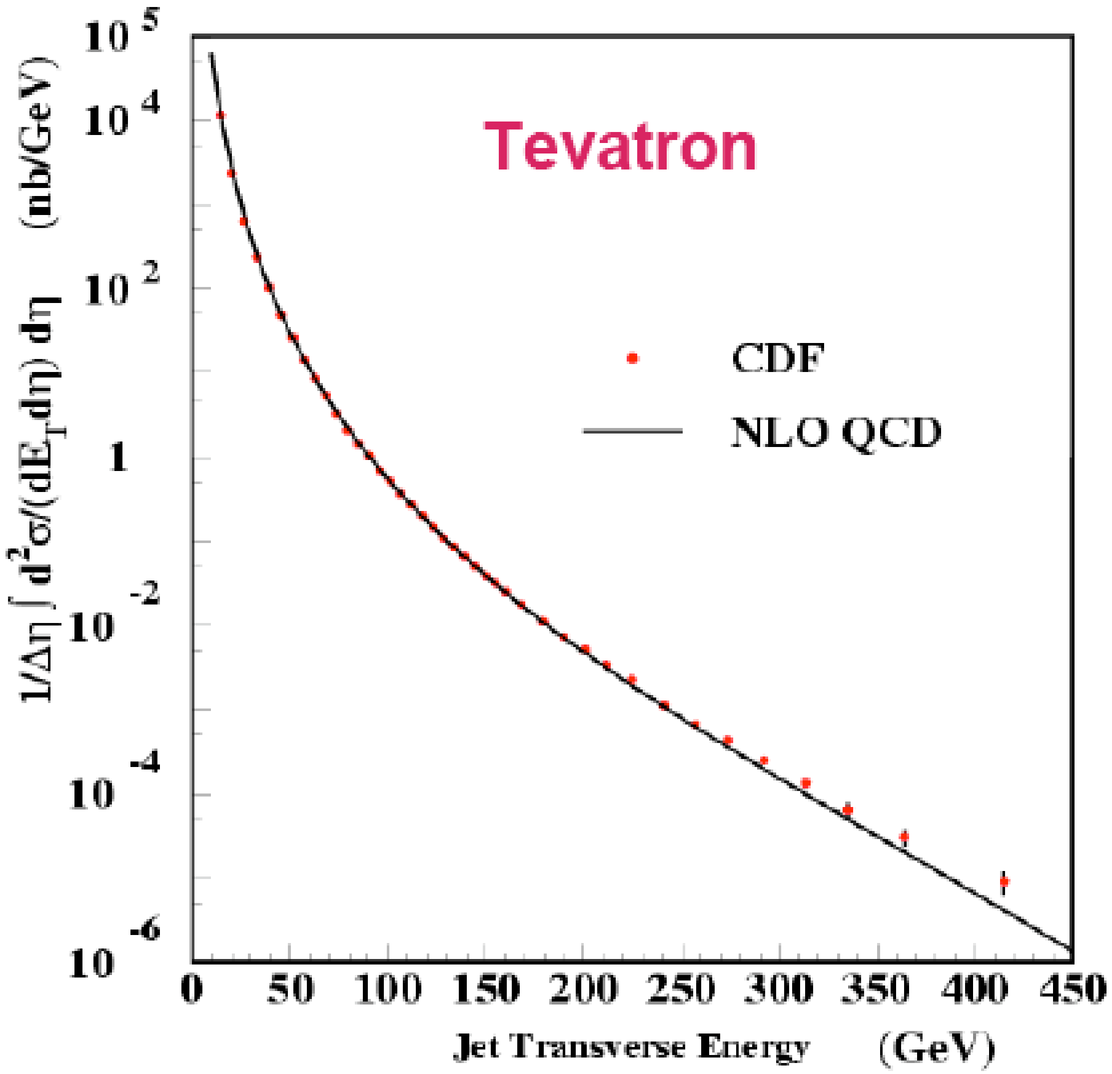
Jets



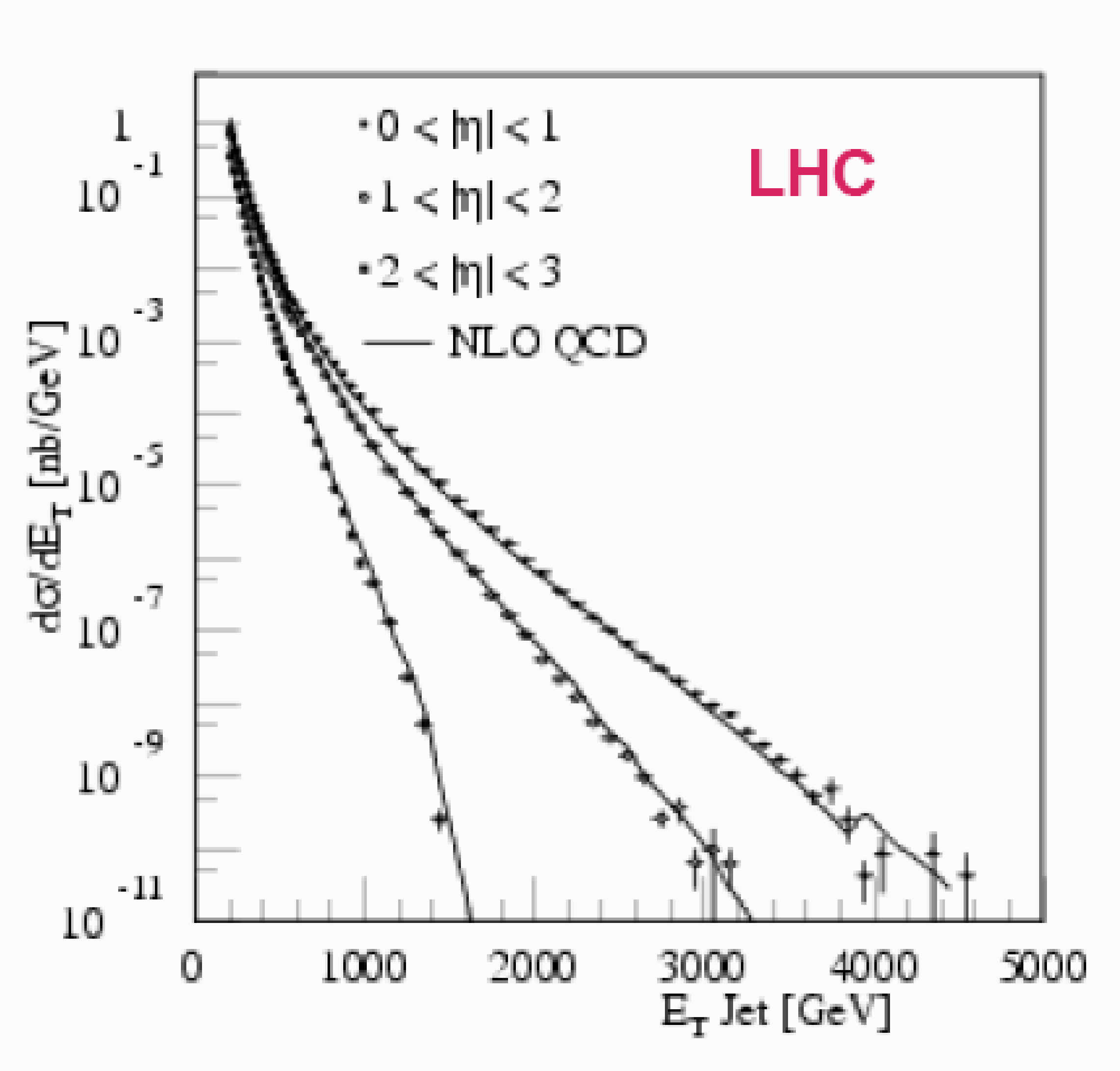
Jets: some facts

- Inclusive production of jets is the largest component of high-Q^2 phenomena in hadron collisions.
- QCD prediction are known up to NLO accuracy only for 2 and 3 jet production.
- Intrinsic theoretical uncertainty (at NLO) is approximately 10%
- Uncertainty due to the knowledge of parton densities varies from 5-10% (at low transverse momentum) to 100% at very high p_T corresponding to high-x gluons.
- Jets are used
  - as probes of the quark structure : possible substructure implies departures from point-like behaviour
  - as probes of new particles : peak in the invariant masss of a di-jet
  - for jet-spectroscopy : increased rate of n-jet ⇒ decay of very heavy hadronic particles into cascades.

From TEV to LHC: inclusive JET



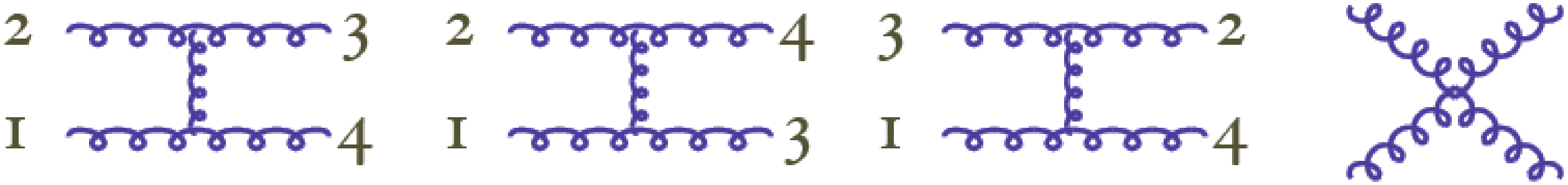
Impressive agreement over 9 orders of magnitude! At high E$_T$ statistically limited. Theoretical uncertaintes coming from high-x gluon pdf. Main Exp systematics form jet energy scale.



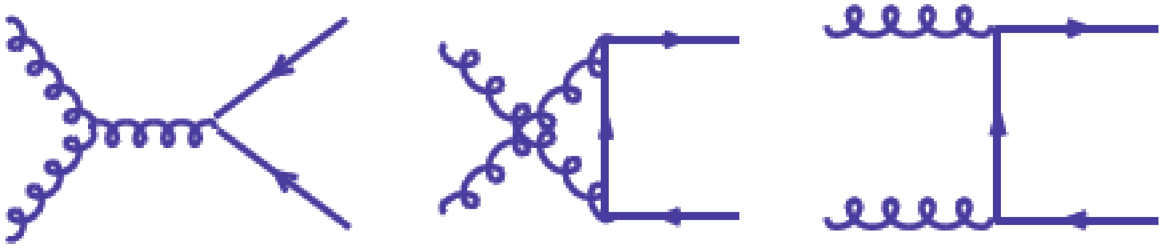
Enormous rates (10^3 events/s with E$_T$>100 GeV).
How to calibrate jet energy scale?
Z+jet and γ+jet don't give enough events at 1 TeV.

Jets: 2 →2 subprocs

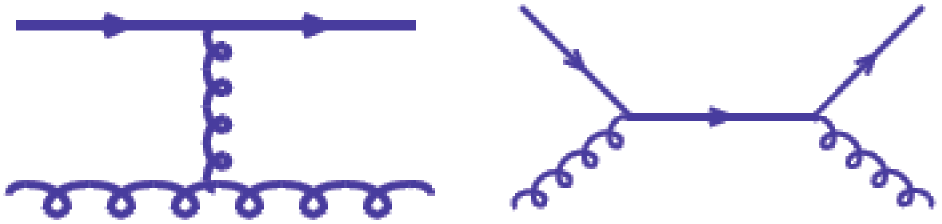
gg → gg



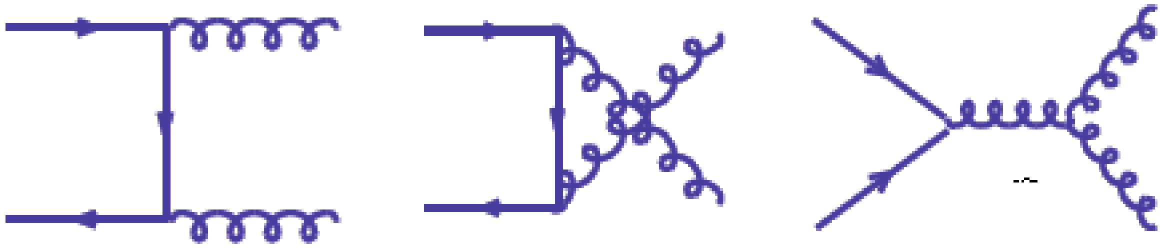
gg → $q\bar{q}$



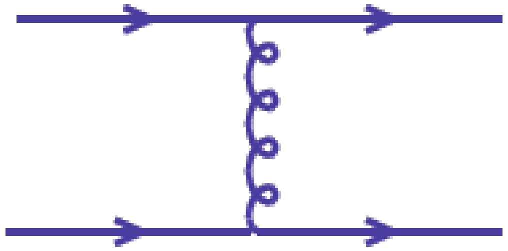
qg→qg



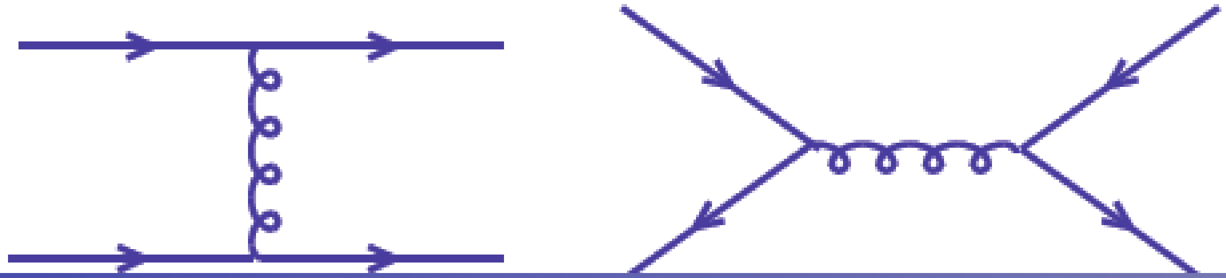
$q\bar{q}$→gg



qq’→qq’



qq→qq



Jets: 2 →2 subprocs

Process	$\overline{\Sigma}\lvert M\rvert^2/g^4$	$\theta=\pi/2$
$qq' \to qq'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$qq \to qq$	$\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}\right]$	3.26
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\bar{q} \to q\bar{q}$	$\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right]$	2.59
$q\bar{q} \to gg$	$\left[\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$	1.04
$gg \to q\bar{q}$	$\left[\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$	0.15
$gq \to gq$	$\left[-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right]$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$	30.4

Dijet differential rate

$$d[PS] = \frac{d^3p_1}{(2\pi)^2 2p_1^0}\frac{d^3p_2}{(2\pi)^2 2p_2^0}(2\pi)^4\delta^4(P_{in}-P_{out})\,dx_1\,dx_2$$

$$\text{(a)}\quad \delta(E_{in}-E_{out})\,\delta(P^z_{in}-P^z_{out})\,dx_1\,dx_2 = \frac{1}{2E^2_{beam}}$$

$$\text{(b)}\quad \frac{dp^z}{p^0} = dy \equiv d\eta$$

$$d[PS] = \frac{1}{4\pi S}p_T\,dp_T\,d\eta_1\,d\eta_2$$

$$\frac{d^3\sigma}{dp_T d\eta_1 d\eta_2} = \frac{p_T}{4\pi S}\sum_{i,j} f_i(x_1)\,f_j(x_2)\frac{1}{2\hat{s}}\overline{\sum_{kl}}|M(ij\to kl)|^2$$

The measurement of p_T and rapidities for a dijet final state uniquely determines the parton momenta x_1 and x_2. Knowledge of the partonic cross-section allows therefore the determination of the partonic densities f(x).

Dijets to probe the pdf's.

In the case of two jets
we can write:

$$x_{1,2} = \frac{p_T}{E_{beam}} \cosh y^* \, e^{\pm y_b}$$

where

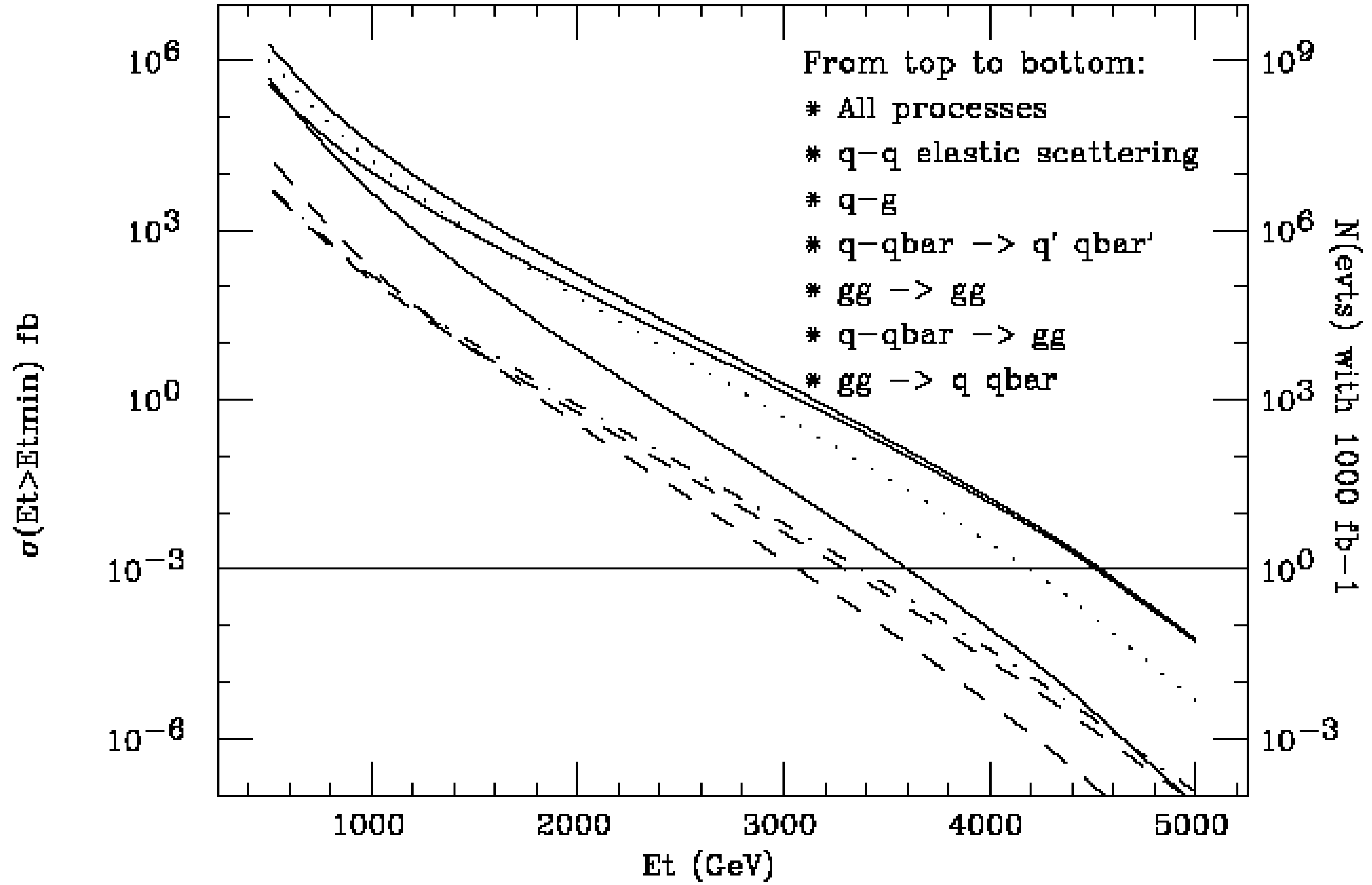
$$y^* = \frac{\eta_1 - \eta_2}{2}, \quad y_b = \frac{\eta_1 + \eta_2}{2}$$

We can therefore reach large values of x either by selecting large invariant mass events:

$$\frac{p_T}{E_{beam}} \cosh y^* \equiv \sqrt{\tau} \to 1$$

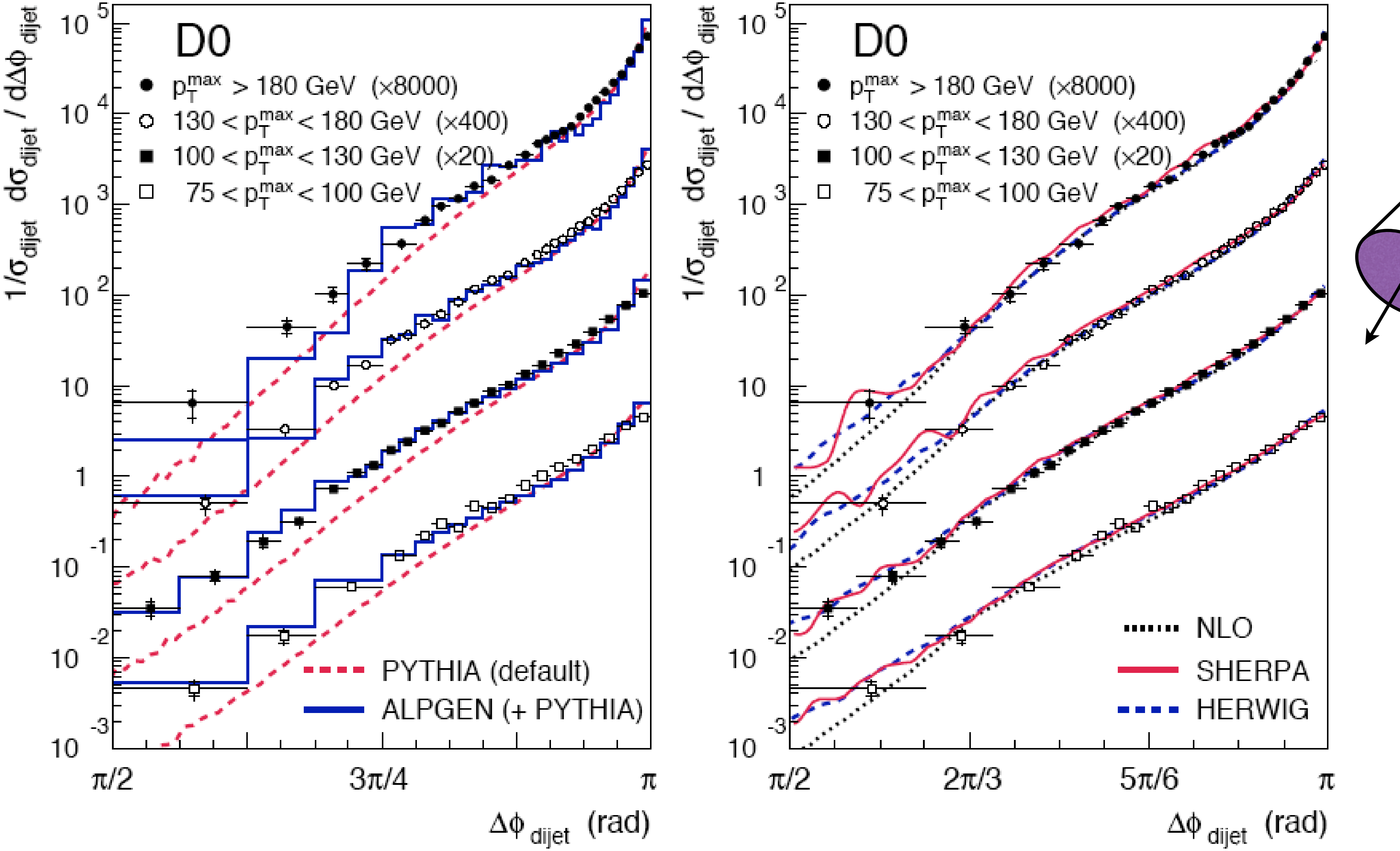
Or by selecting low-mass event, but with large boosts in the positive or negative directions. In this case we probe the large-x with events where possible new physics is absent, thus setting consistent constraints on the behaviour of the cross-section in the high-mass region which could hide new phenomena.

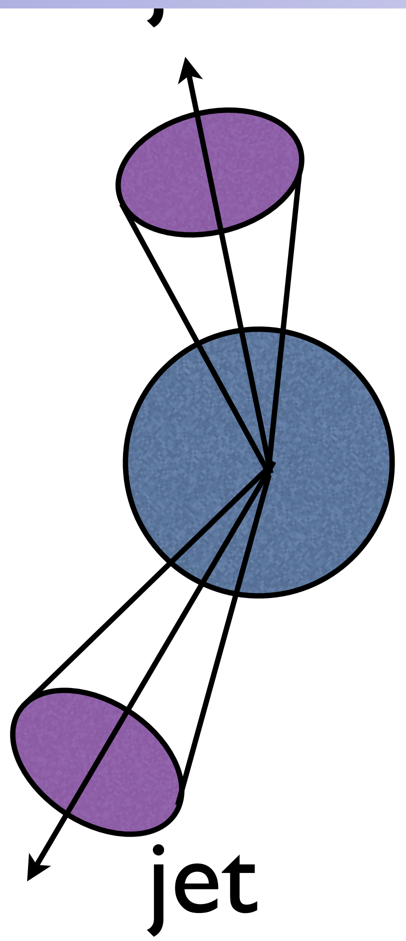
Jets: rates at the LHC by subprocess



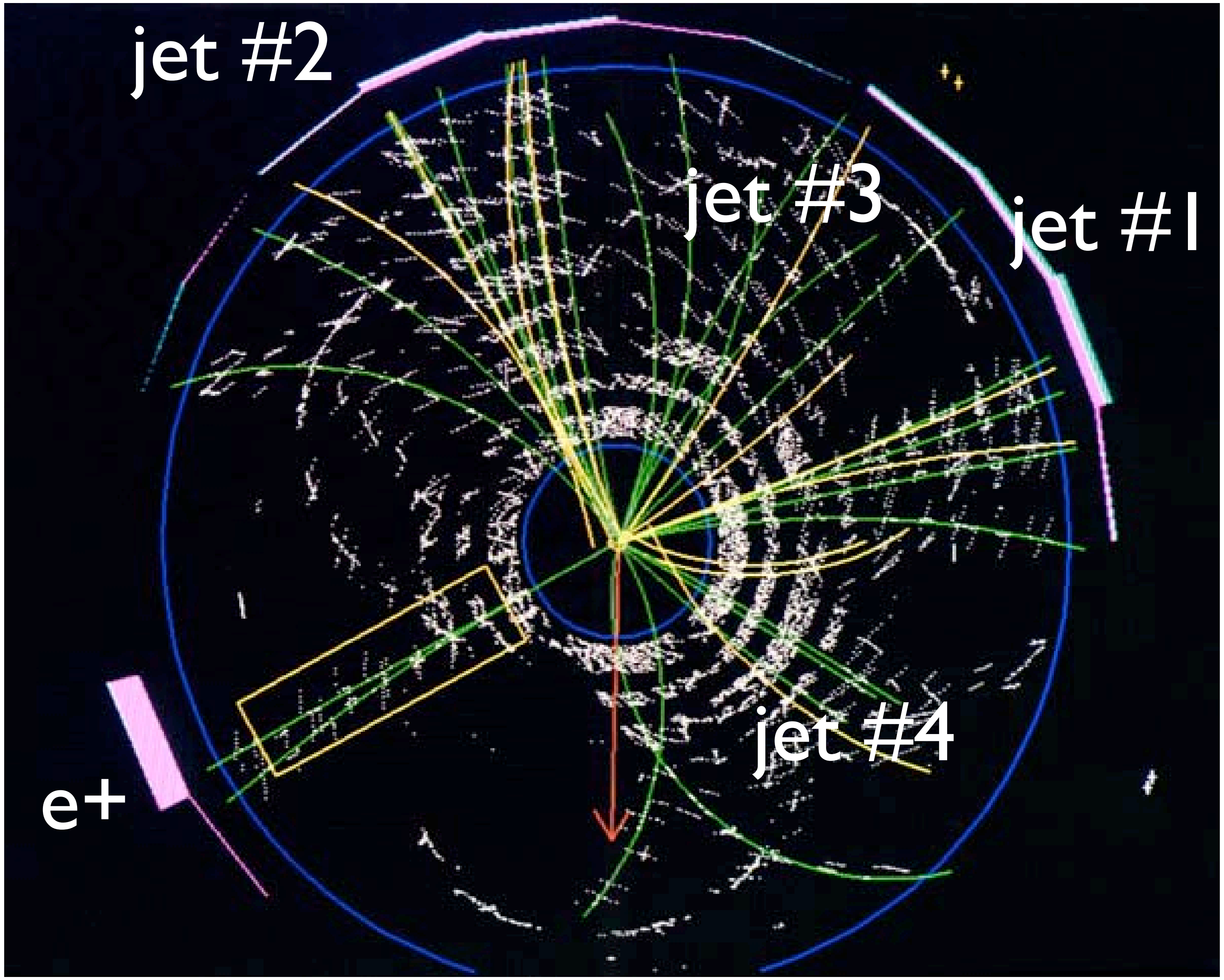
The presence of a quark substructure would manifest itself via a contact interaction (as in Fermi's theory of weak interactions). One one side these new interactions would lead to an increase in cross-section, on the other they would affect the jets' angular distributions. In the di-jet c.m.s. frame, QCD implies Rutherford law, and extra point-like interactions can then be isolated through a fit. With a statistics of 300 fb^{-1}, limits on the scale of the new interactions in excess of 40 TeV should be reached.

Angular decorrelations pp→2j events



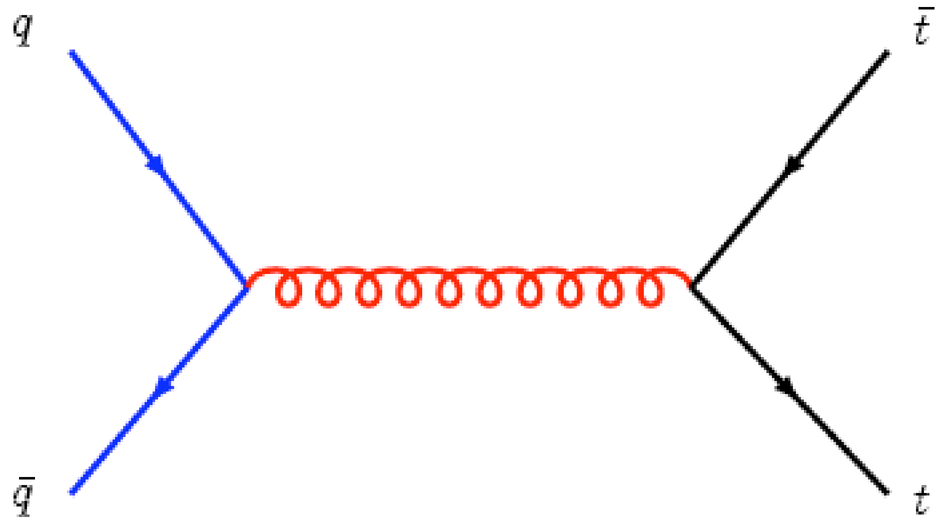


Top



Tevatron vs LHC

Tevatron



85% of the total cross section

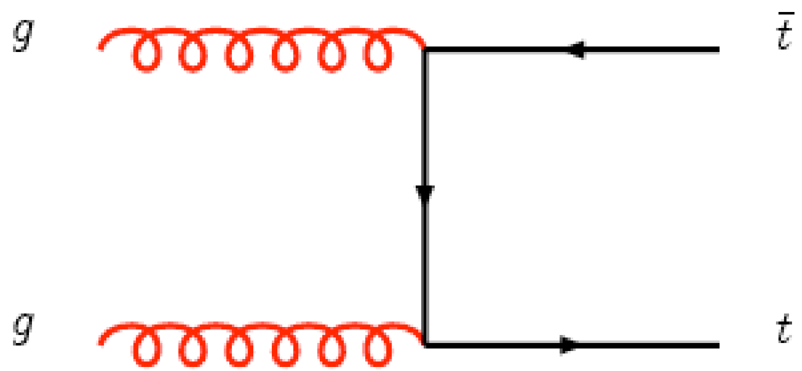
10 tt pairs per day

60% of the time there is extra radiation so that pt(tt)>15 GeV.

tt are produced closed to threshold, in a $^3S_1[8]$ state. Same spin directions. 100% correlated in the off-diagonal basis.

Worry because of the backgrounds: (W+jets, WQ+jets,WW+jets)

LHC



90% of the total cross section

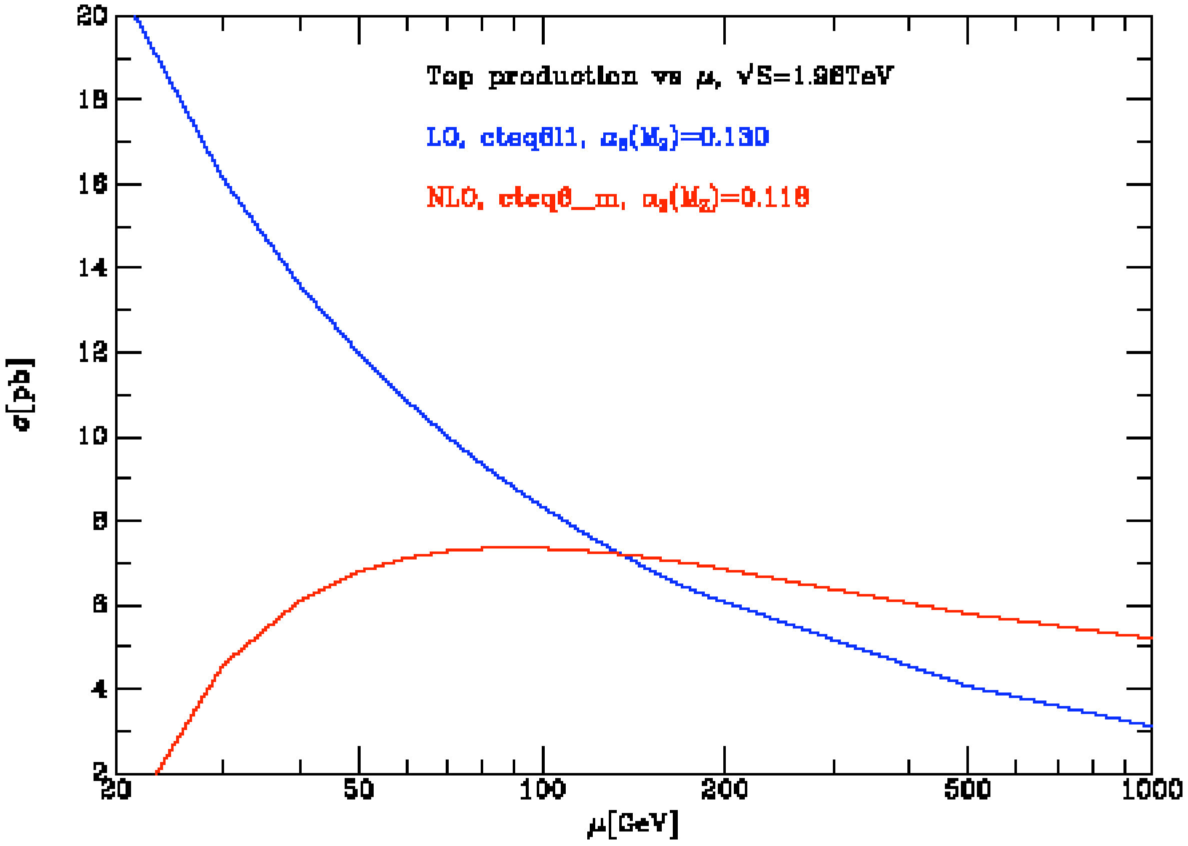
1 tt pair per second

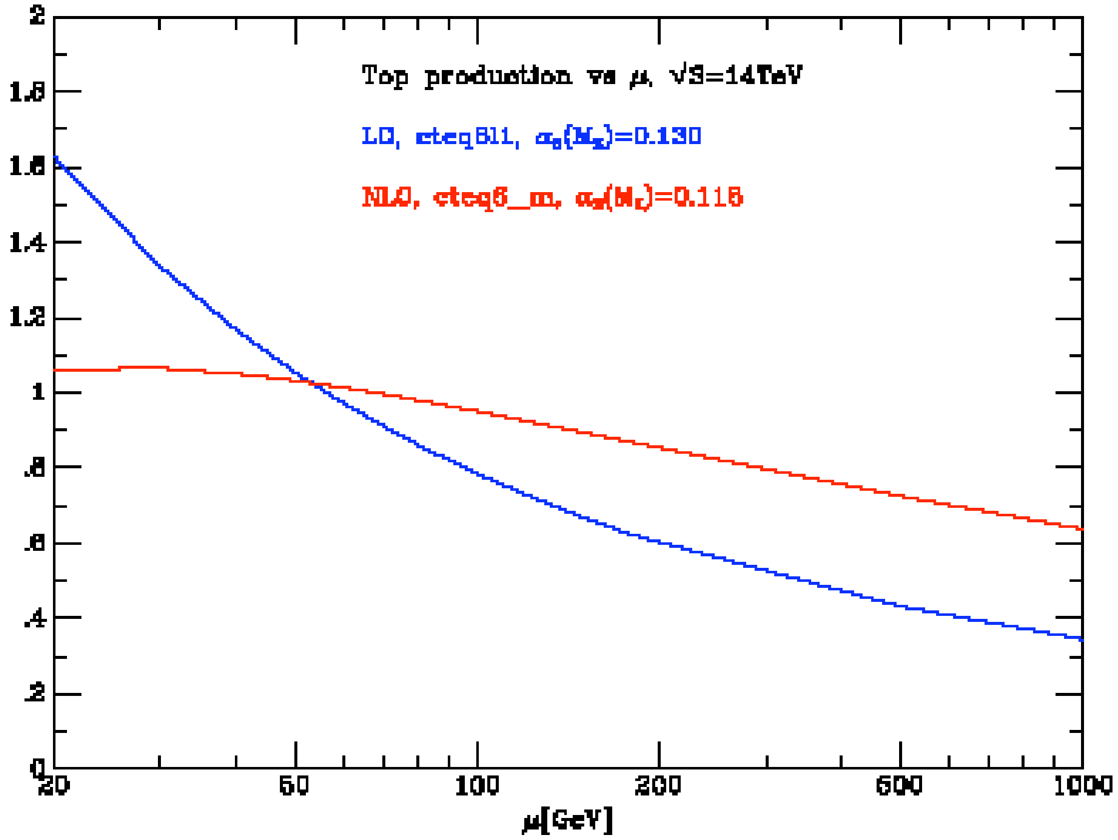
Almost 70% of the time there is extra radiation so that pt(tt)>30 GeV.

tt can be easily produced away from threshold. On threshold they are $^1S_0$ state, with opposite spin directions. No 100% correlation.

Worry because IT is a background!

Tevatron vs LHC





Inclusion of higher order corrections leads to a stabilization of the prediction.
At the LHC scale dependence is more difficult to estimate.

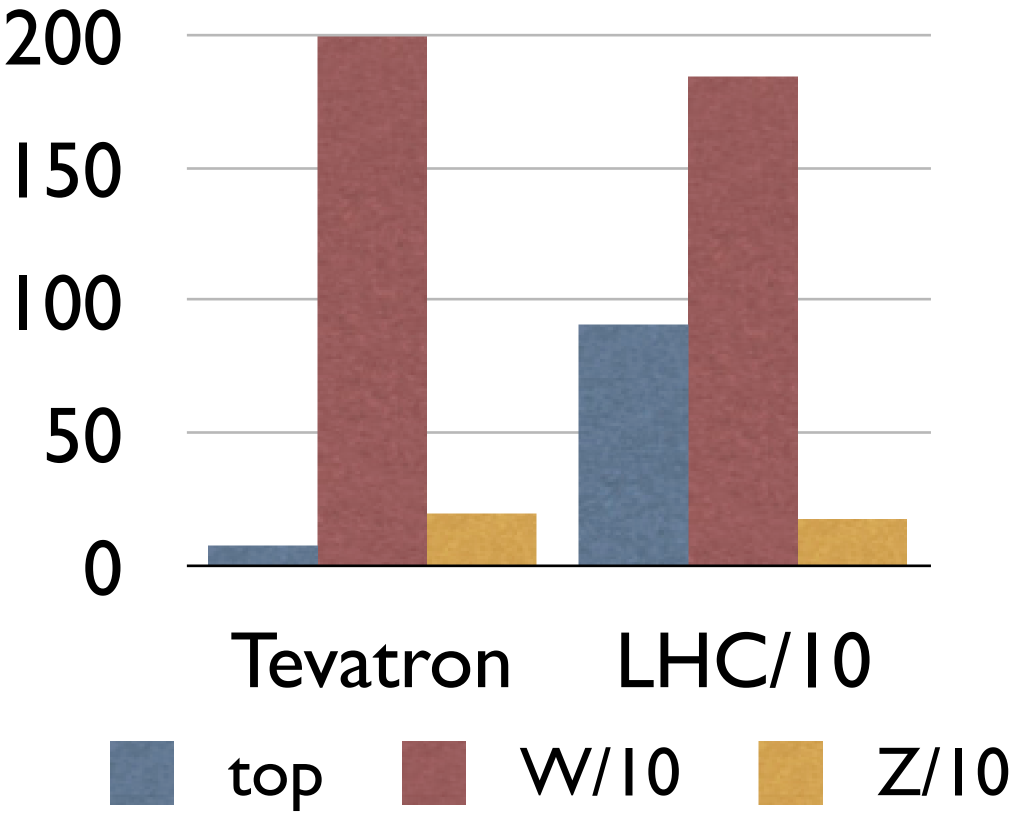
Results including higher order corrections (partly NNLO now available).

Cross sections : from Tevatron to the LHC

Total cross section for ttbar increases by a factor of 100, while Drell-Yan only by a factor of 10.

Top will be one of the major background to any new physics!

However, extra hard radiation is much easier at the LHC than at the Tevatron!



pb	tt	$W^{+-} \rightarrow e^{+-} \nu_e$ inclusive	$Z \rightarrow e^+ e^-$ inclusive	$W \rightarrow e^{+-} \nu_e$ + 4jets		$Z \rightarrow e^+ e^-$ + 4jets	
TeV	7.6	2000	200	0.98		0.096	
LHC	910	18500	1800	220	(20)	21	(2.1)
Gain	120	9	9	220	(21)	220	(22)

pt(j)>20 (50) GeV , |eta(j)|<3, DeltaR(jj)>0.7

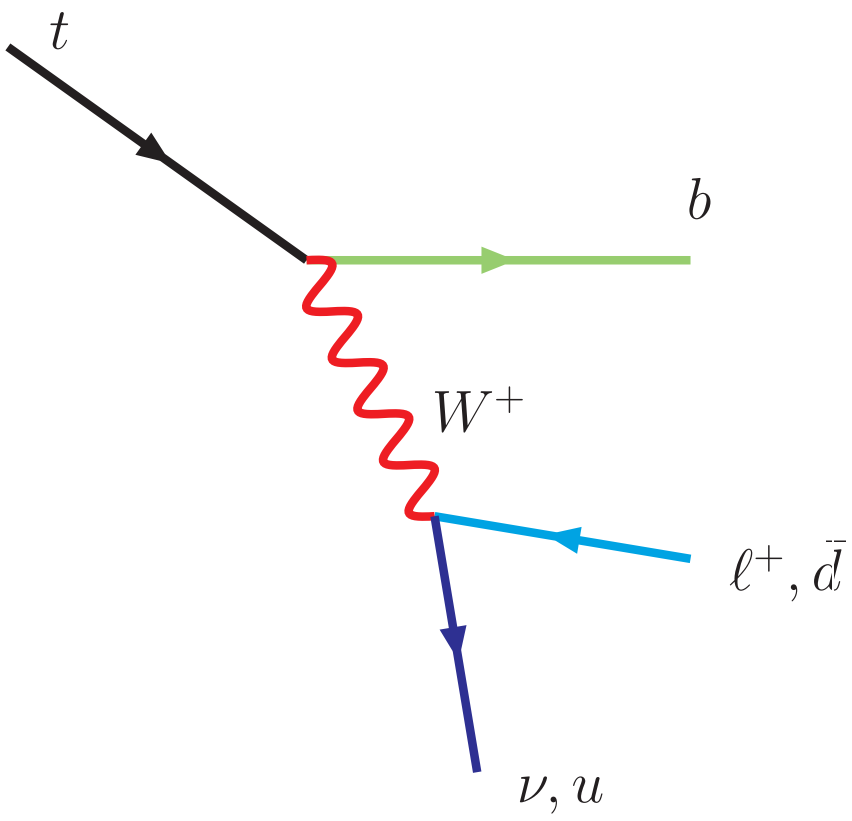
tt as Background

At the LHC, many measurements will need a good understanding and control of tt events.

A few examples:

- tt in gg→H and qq→Hqq with H→WW
- tt in single top measurements
- tt+jets and ttbb for ttH
- tt+jets and ttW for SUSY searches (gluino pairs, stop pairs, tH^+....)

Top decay: sm br's



Top can decay into a real W ⇒

$\Gamma \approx G_F m_t^3 |V_{tb}|^2 >> \Lambda_{QCD}$ ⇒

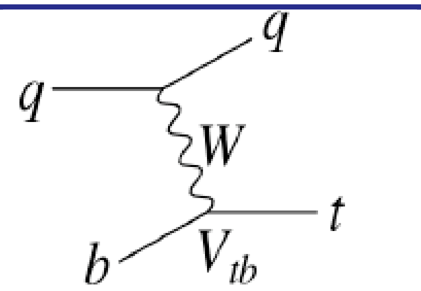
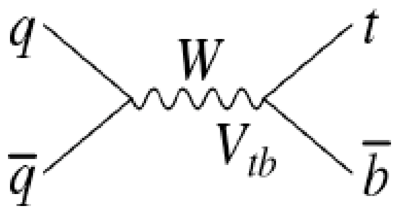
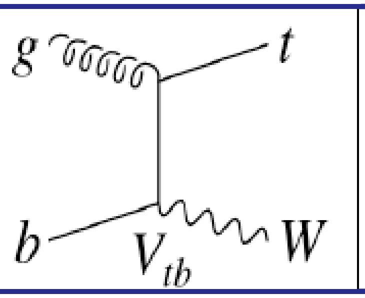
Very short life. Top is the only quark that does not feel non perturbative QCD effects! No top-hadrons, no top-spectroscopy but a ``clean'' quark.

In an experiment one is sensitive not to the total width but to the branching ratio:

$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

CDF has performed such a measurement:
R=0.94 does only tell us that $V_{tb} >> V_{td}, V_{ts}$

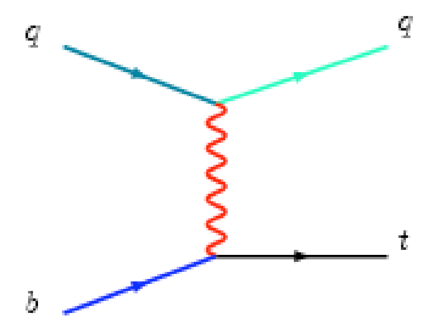
Single top

Process	Diagram	Accuracy	CTEQ6M, mt=178 GeV,th err≅10% σ (pb)	
			TeV II	LHC
t-channel		NLO [Stelzer, Sullivan, Willenbrock. 1997]	1.85	239
s-channel		(N)NLO [Smith, Willenbrock. 1996 Chetyrkin, Steinhauser. 2001]	0.82	9.8
tW		NLO [Campbell, Tramontano. ‘05]	0.129	64

All signals available in MCFM (Campbell, Ellis) and in MC@NLO (Frixione, Webber). Most of the backgrounds are also known at NLO. However, analysis still rely on LO calculations for the heavy-quark fractions in W+jets events (largest background) ⇒ room for improvement.

A closer look at t & s channels

t channel



SM info

Largest rate, dominant at the LHC, where 62% top, 38% anti-top.

$\sigma \propto |Vtb|^2$.

Forward jet in final state, top central, sometimes one extra forward bottom. FB asymmetric at the Tevatron. Main background W+Q's+jet (and tt at the LHC).

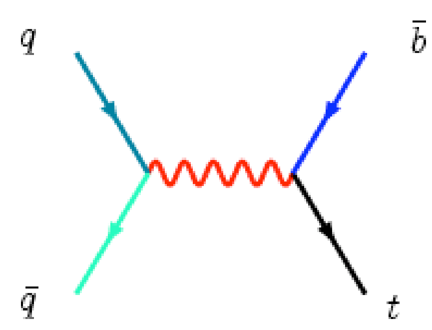
Top is polarized along spectator jet (most of the times) in the 2→2 configuration.

BSM window

Sensitive to new production modes, through FCNC (qc→qt).

Associated Higgs production in SUSY.

s channel



SM info

Smallest at the LHC, where 63% top, 37% anti-top.

$\sigma \propto |Vtb|^2$

Very well known. DY might be used for normalization.

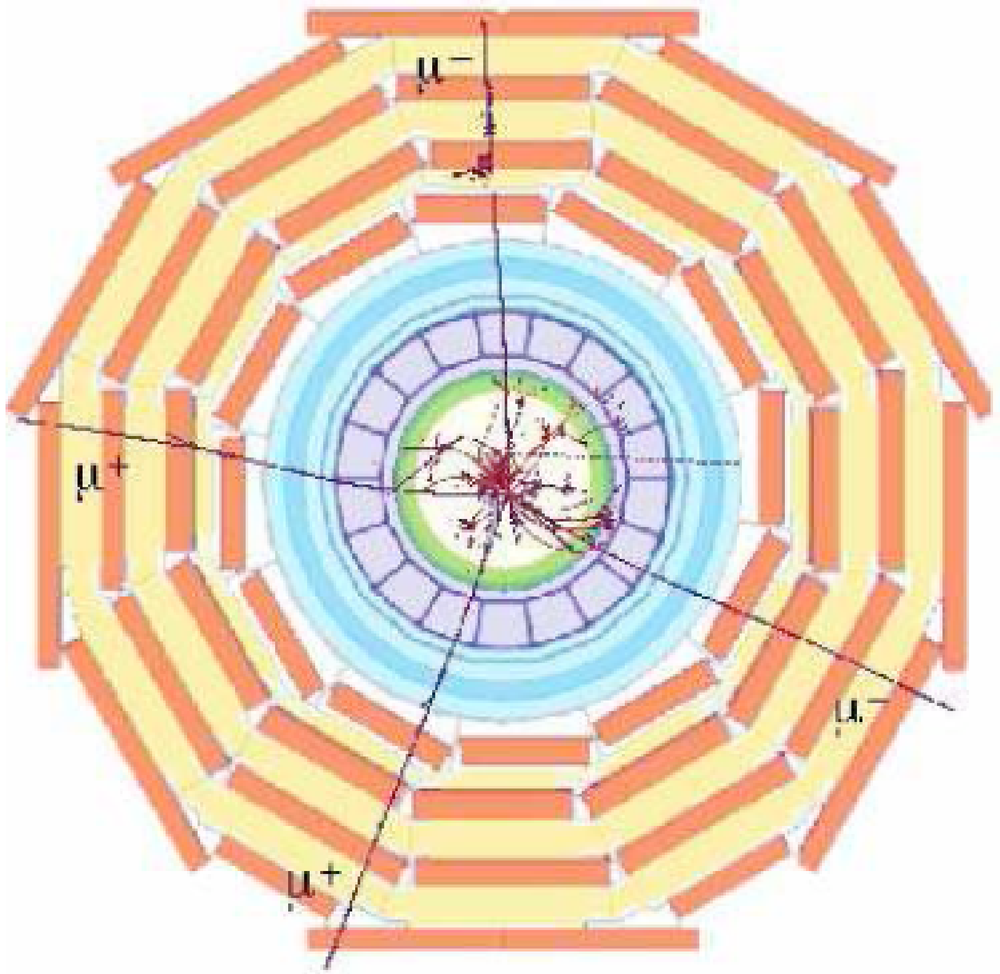
Central high-pt b-jet. Main backgrounds: tt, tj, and W+Q's+jets.

Top is polarized along beam axis at the Tevatron.

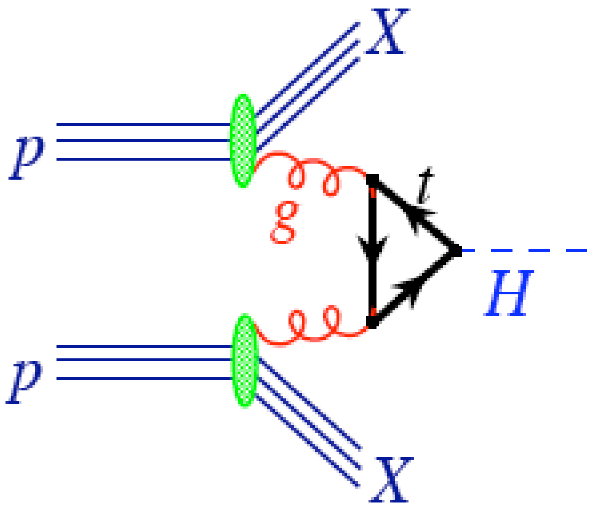
BSM window

Sensitive to vector (extra Z) and scalar (top pions) resonances.
Spin correlations to study the handness of the couplings.

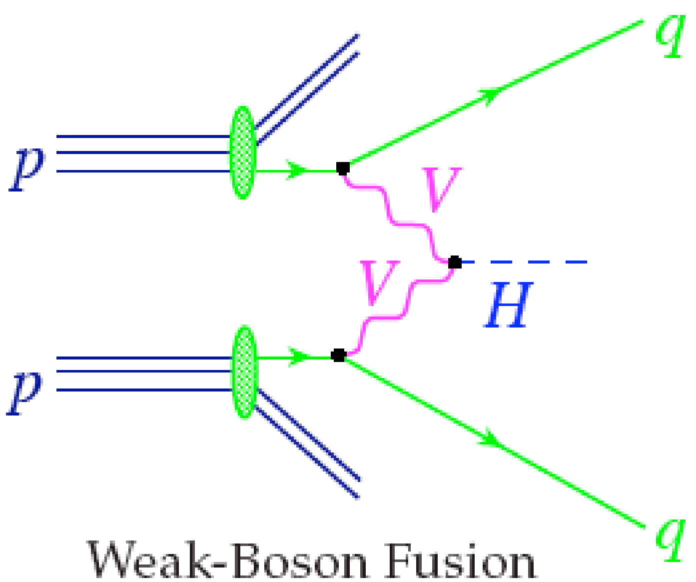
Higgs



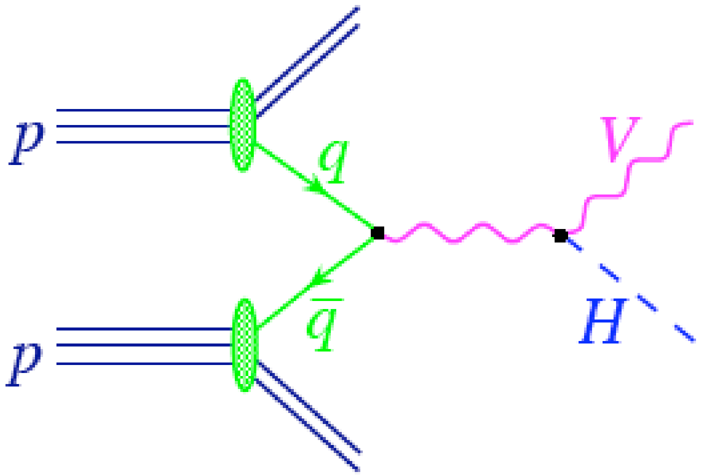
Higgs production



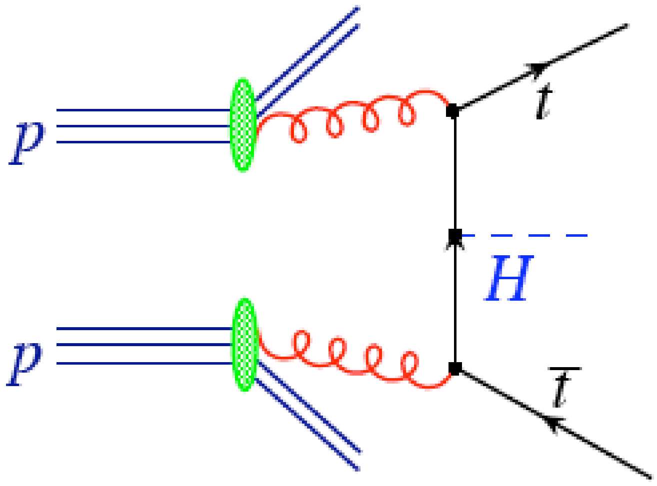
Gluon fusion



Weak-Boson Fusion

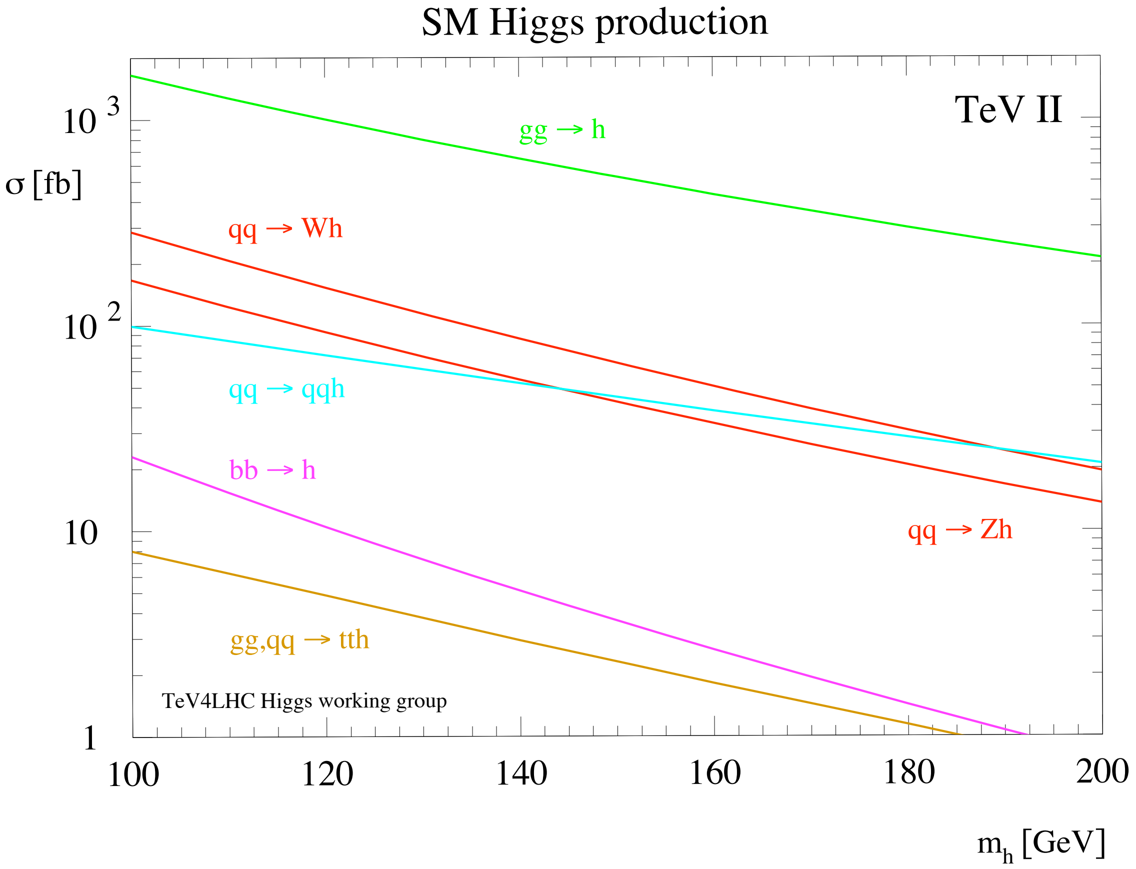


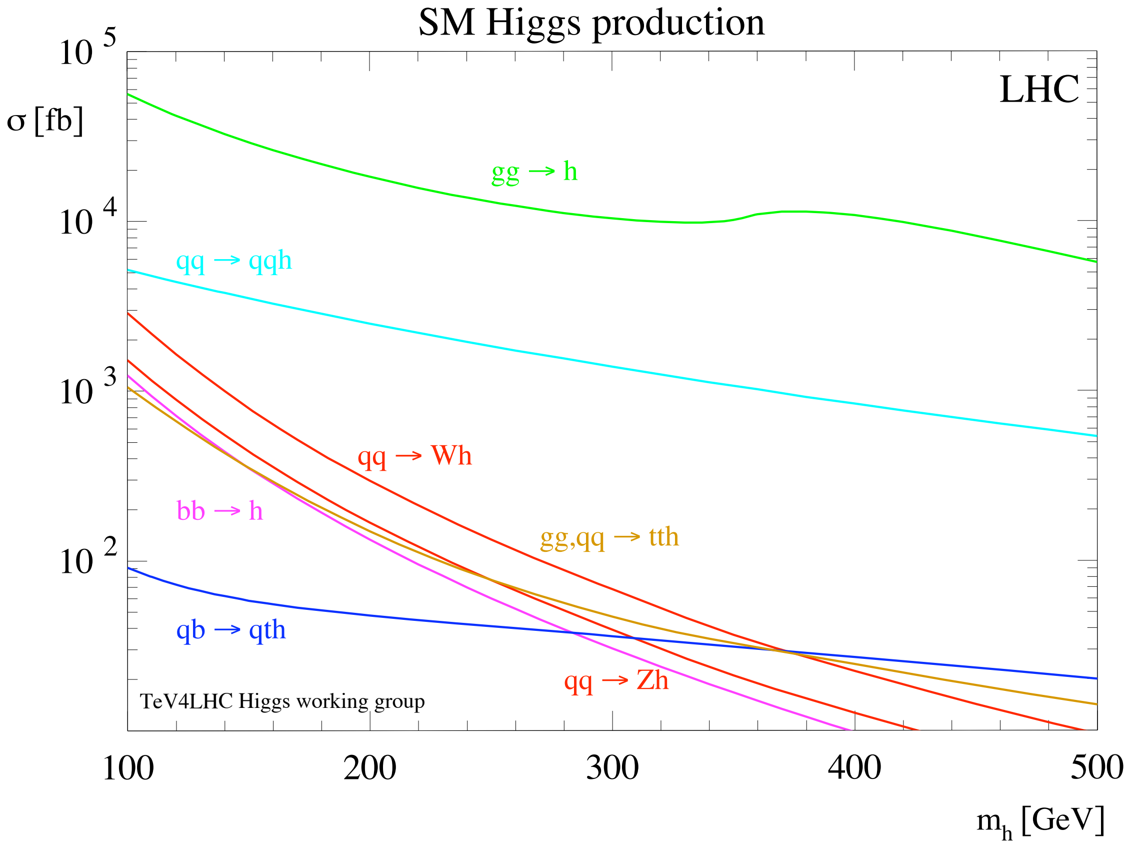
Higgs Strahlung



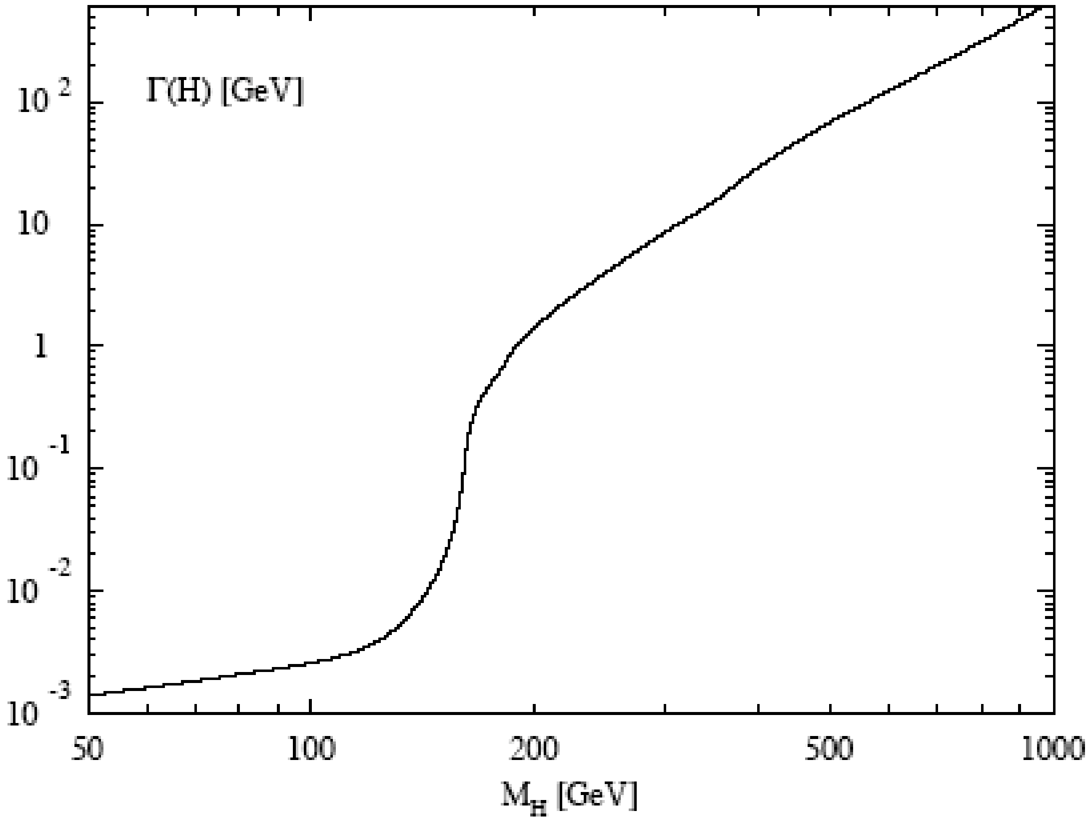
$t\bar{t}H$

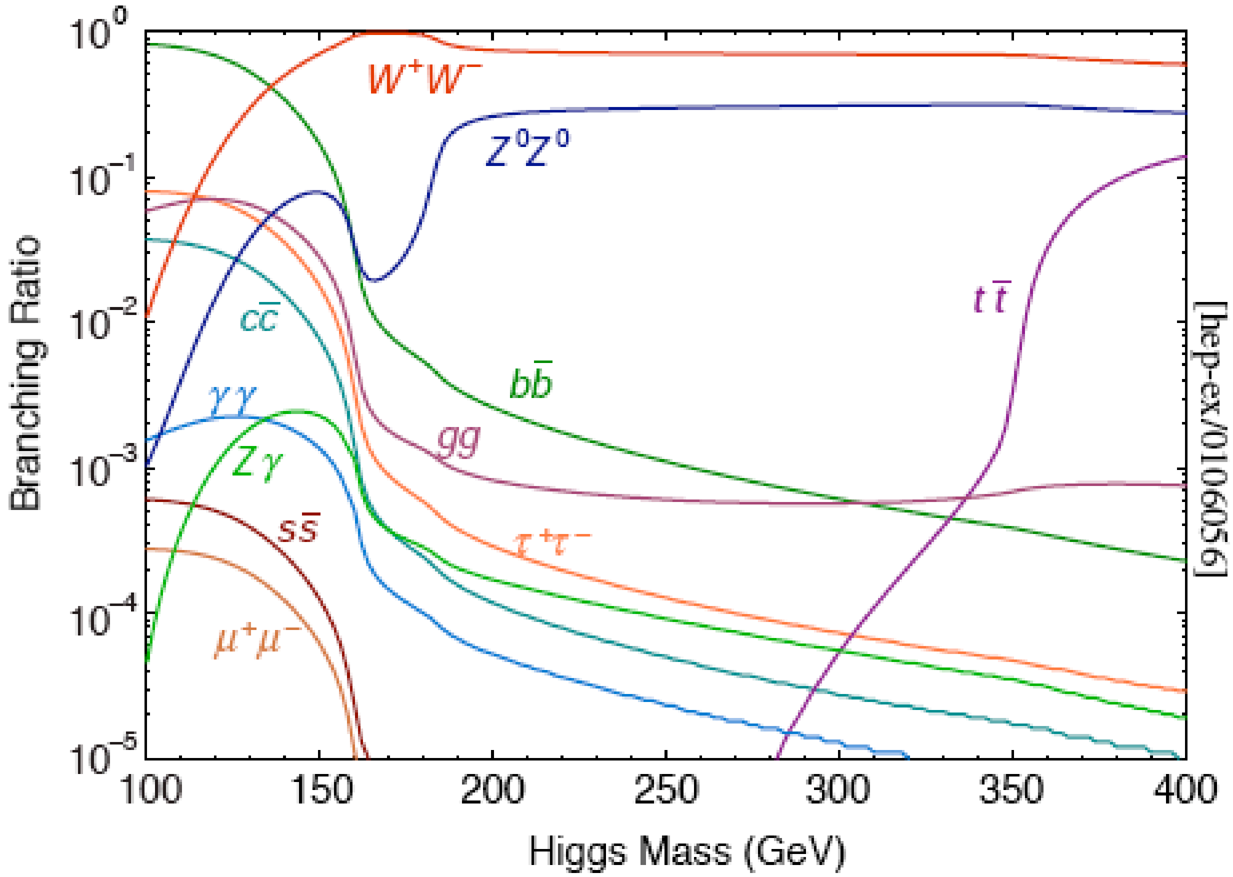
Higgs production





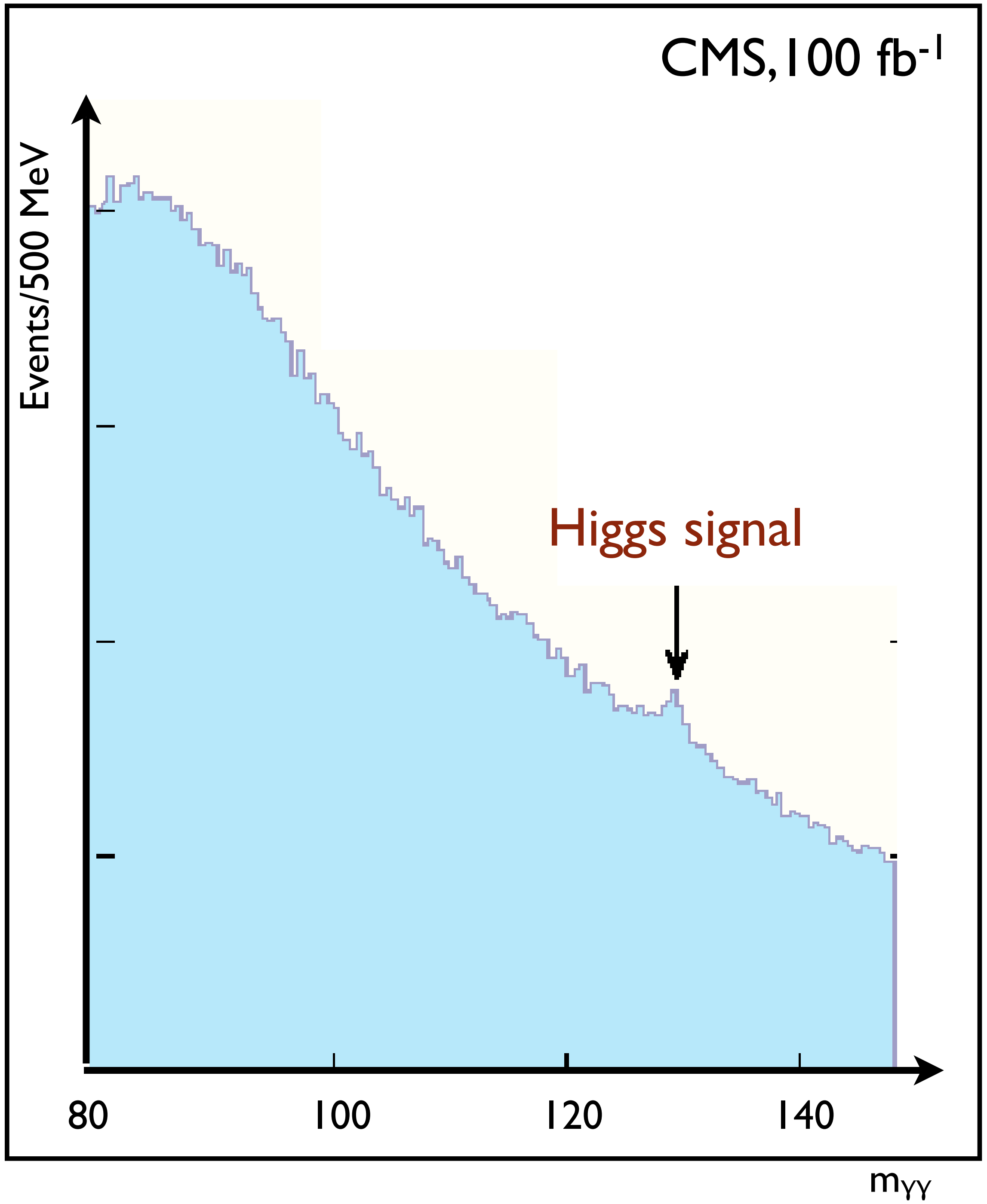
Higgs decay





[hep-ex/0106056]

$gg \to H \to \gamma\gamma$



Huge background from QCD.

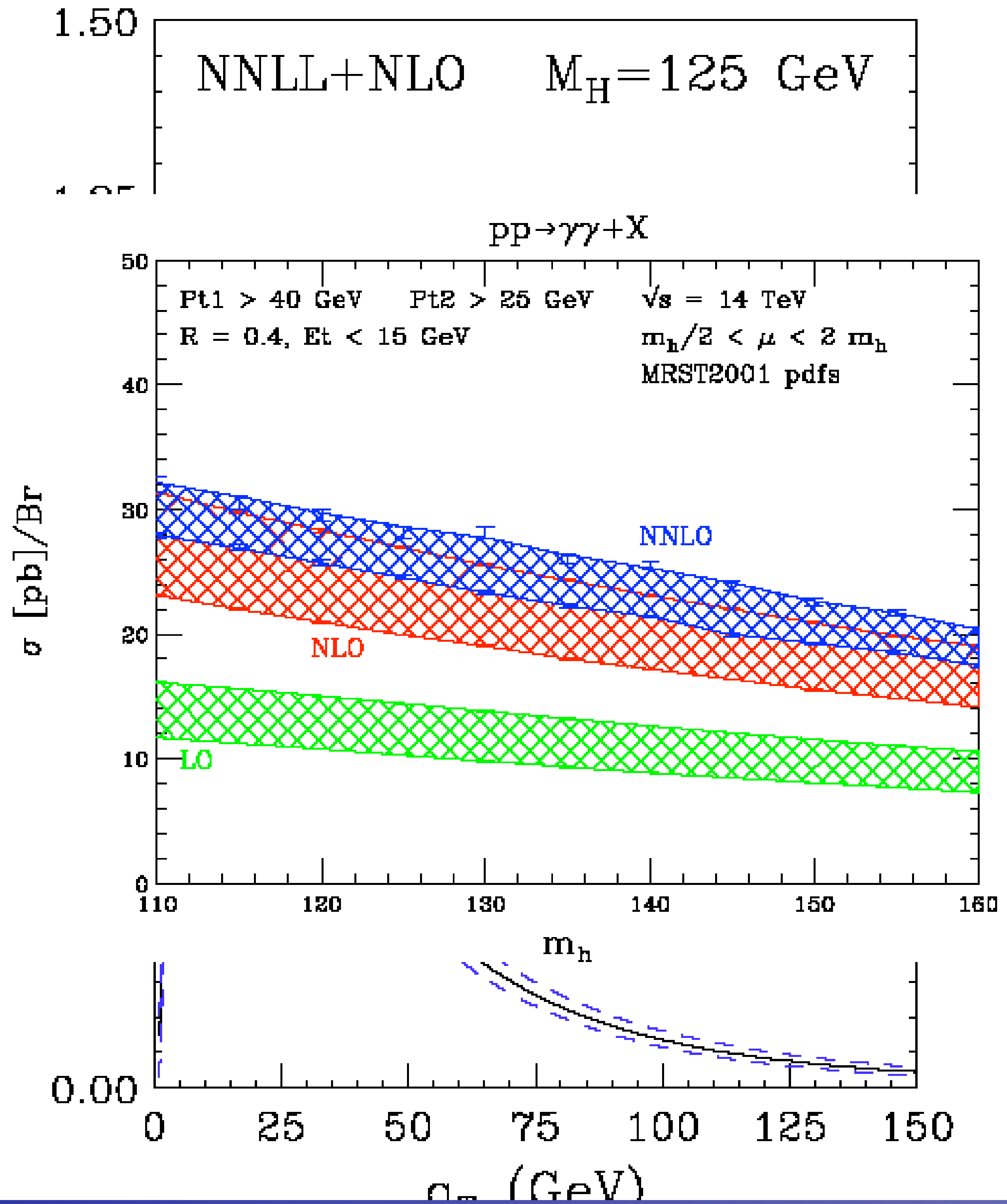
$qq \to \gamma\gamma$ known at NLO (DIPHOX) including fragmentation contributions
[Binoth, Guillet, Pilon, Werlen. 2000]

$gg \to \gamma\gamma$ direct known at NLO (two-loop)
[Bern, Dixon, Schmidt. 2002]

This is an example of a discovery that does not need an accurate theoretical prediction for the background. Data modeling will suffice.

On the other hand, extraction of information about couplings to top and W needs accurate predictions for both the cross section and the branching ratio.

gg→H→γγ



Dominant production mechanism at hadron colliders.
The story of the most accurate prediction in QCD:

QCD corrections:
[Daswon.1991] [Djouadi, Graudenz, Spira, Zerwas. 1991]
[Kramer, Laenen, Spira.1998] [Catani, De Florian, Grazzini.2001]
[Harlander, Kilgore.2001,2002] [Anastasiou, Melnikov.2002]
[Ravindran,Smith, Van Neerven. 2003]
[Catani, De Florian, Grazzini, Nason.2003]

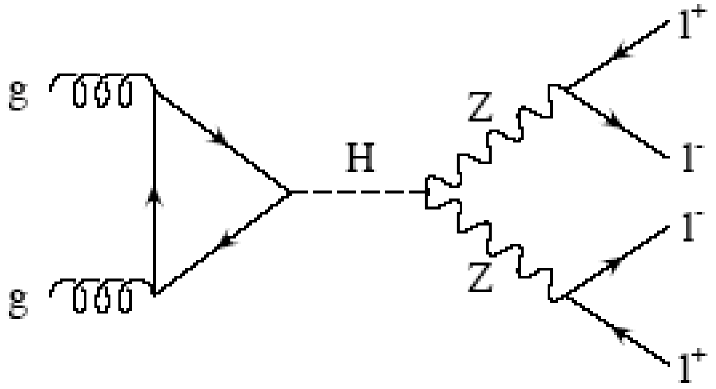
Two-loop EW corrections:
[Djouadi, Gambino, Kniehl. 1998]
[Aglietti, Bonciani, Degrassi, Vicini. 2004]
[Degrassi, FM. 2004]

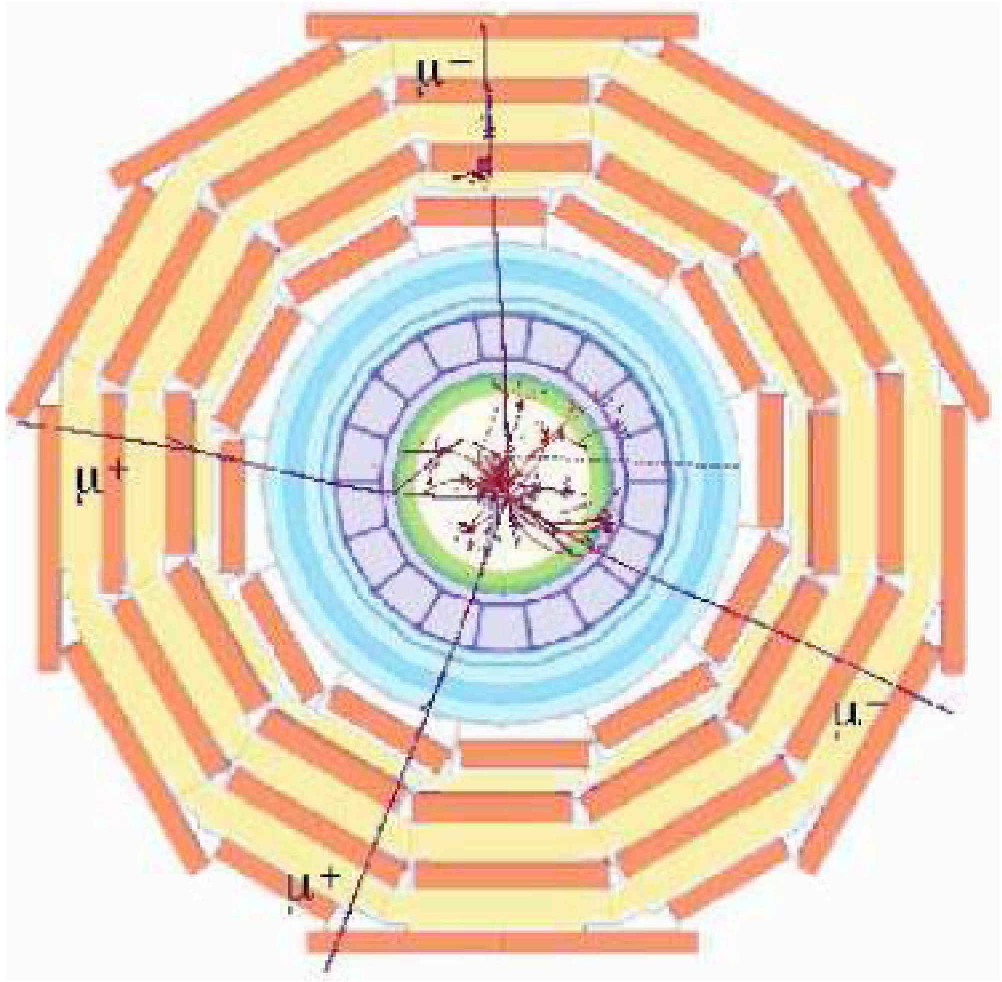
PDF evolution at NNLO ("Guinness of QCD"):
[Moch, Vogt, Vermaseren, 2004]

Best QCD predictions at present:
> Fully exclusive (PS interfaced) prediction at NLO+NLL[Frixione, Webber, 2003]
> Fully exclusive prediction at NNLO (first ever) [Anastasiou, Melnikov, Petriello. 2004]
> Resummed pt distribution at NLO+NNLL [Bozzi, Catani, De Florian, Grazzini, 2005]

gg→H→ZZ→4 leptons

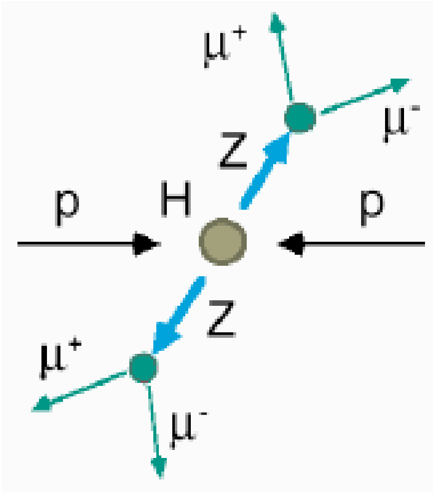
The gold-plated mode

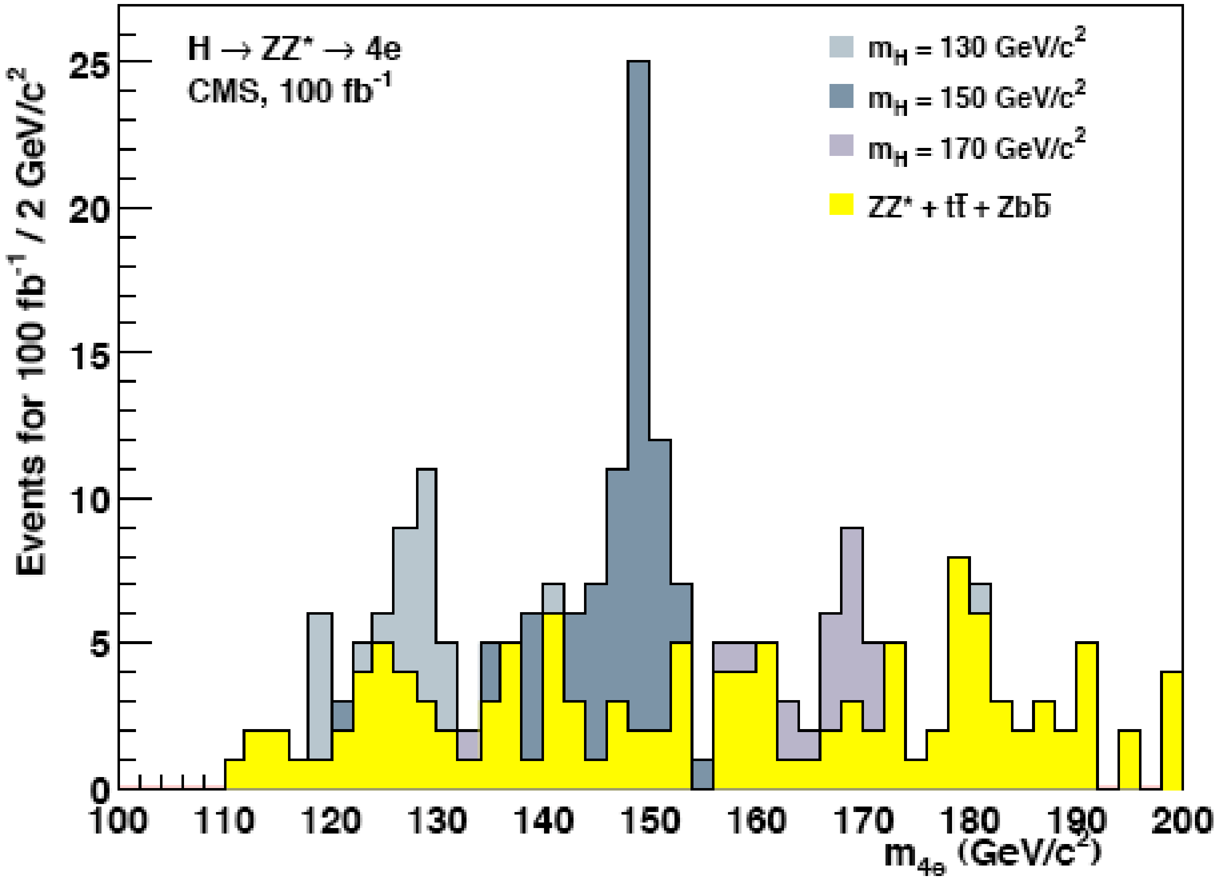




- ✓ This is the most important and clean search mode for $2m_Z < m_H < 600$ GeV.
- ✓ continuum, limited, irreducible background from $q\bar{q} \to ZZ$
- ✗ small $\mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$ (even smaller when $m_H < 2m_Z$)

gg→H→ZZ→4 leptons





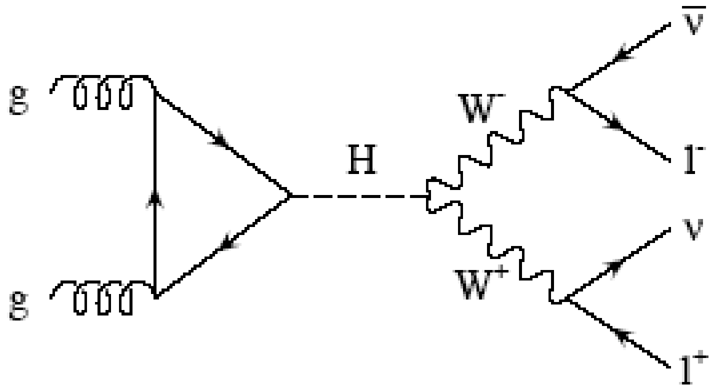
✓ invariant mass of the charged leptons fully reconstructed

For $m_H \approx 0.6$–1 TeV, use the "silver-plated" mode $H \to ZZ \to \nu\bar{\nu}\ell^+\ell^-$

✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$

✓ the large E_T missing allows a measurement of the transverse mass

gg→H→WW→ l+ l- ν ν

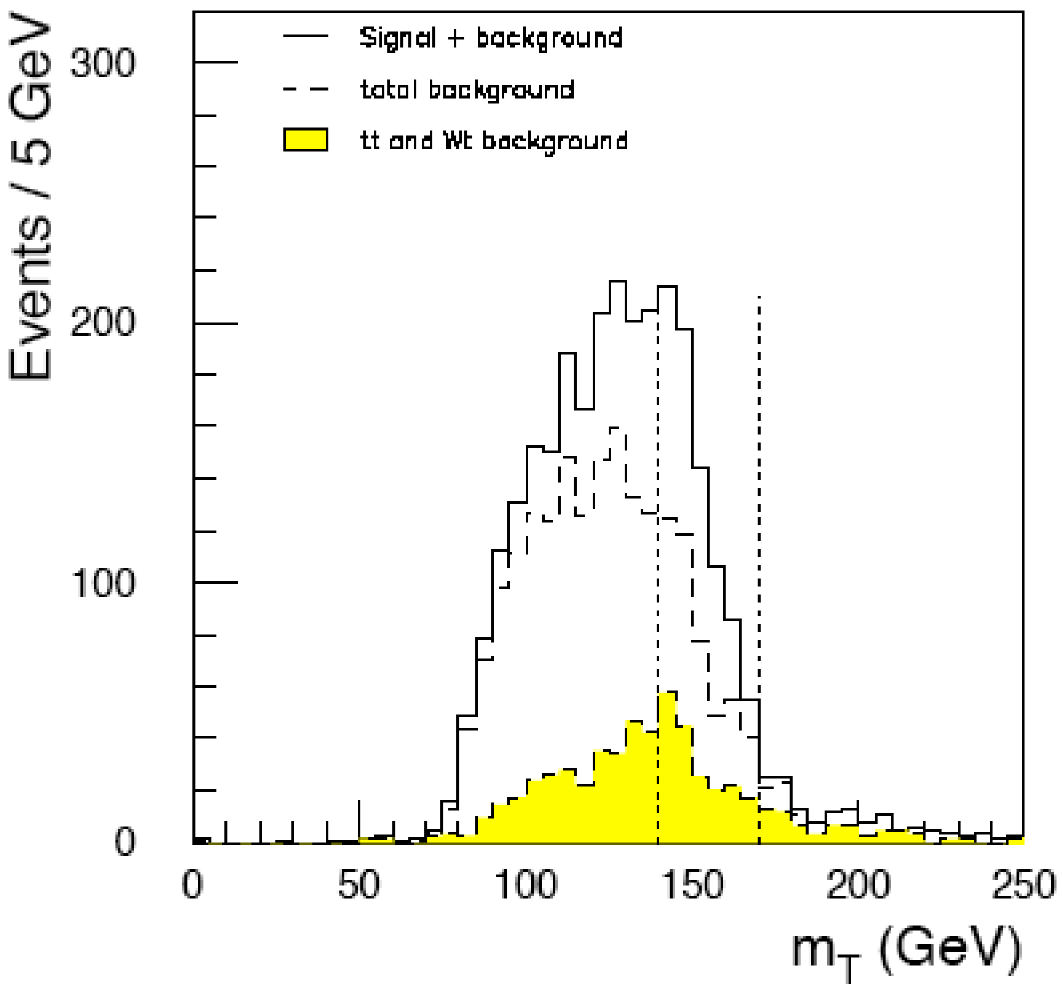


- ✓ Exploit $\ell^+\ell^-$ angular correlations*
- ✓ measure the transverse mass with a Jacobian peak at m_H

$$m_T = \sqrt{2\, p_T^{\ell\ell}\, \not{E}_T\, (1 - \cos(\Delta\Phi))}$$

- ✗ background and signal have similar shape $\Longrightarrow$ must know the background normalization precisely

ATLAS TDR

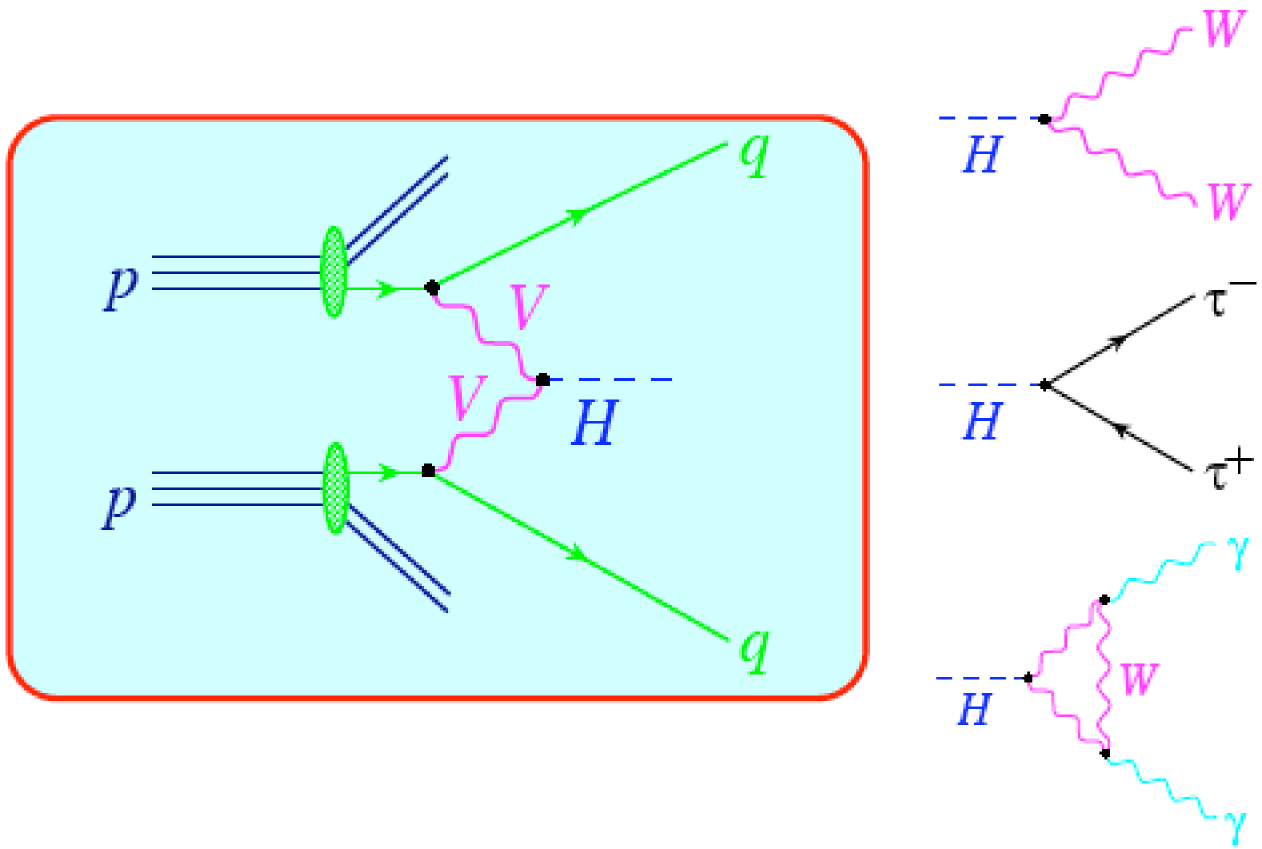


$m_H = 170\,\text{GeV}$

integrated luminosity = 20 fb^{-1}

* The charged leptons tend to go in the same direction... think about an easy argument!

VBF



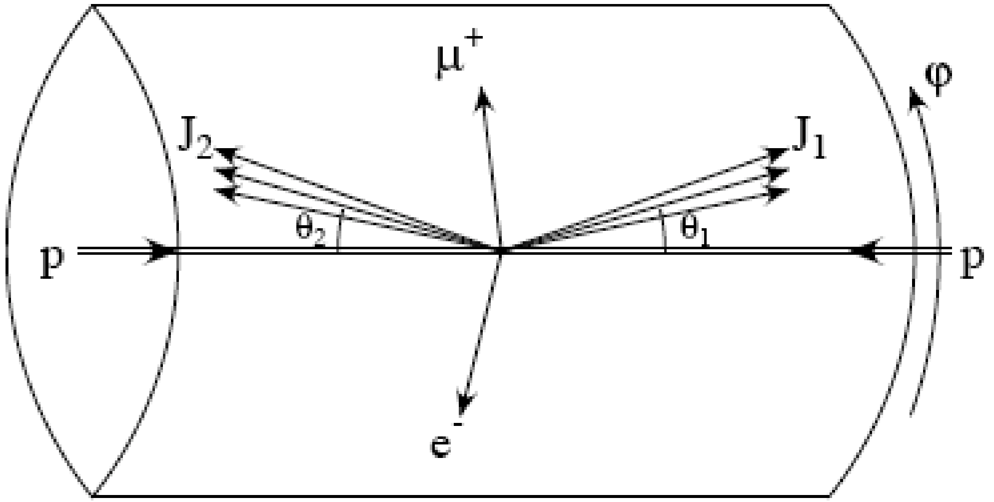
$m_H > 120$ GeV

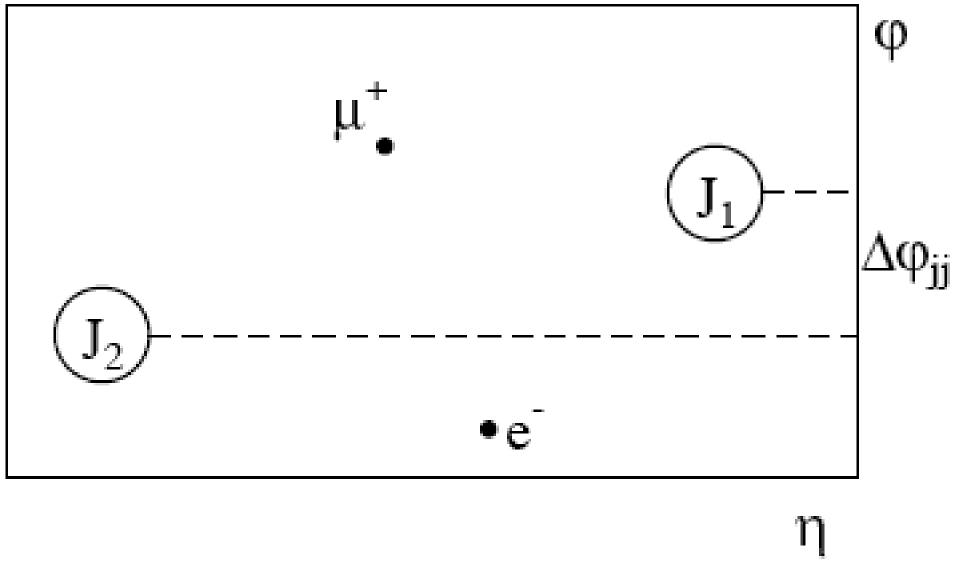
$m_H < 140$ GeV

$m_H < 150$ GeV

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma\times$ BR, of order 10% (sometimes even better).

VBF



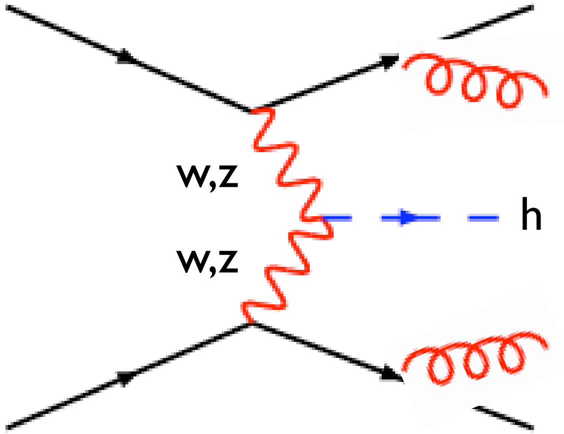


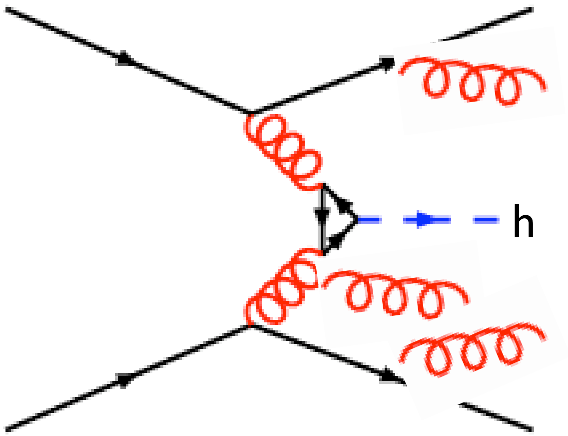
Characteristics:

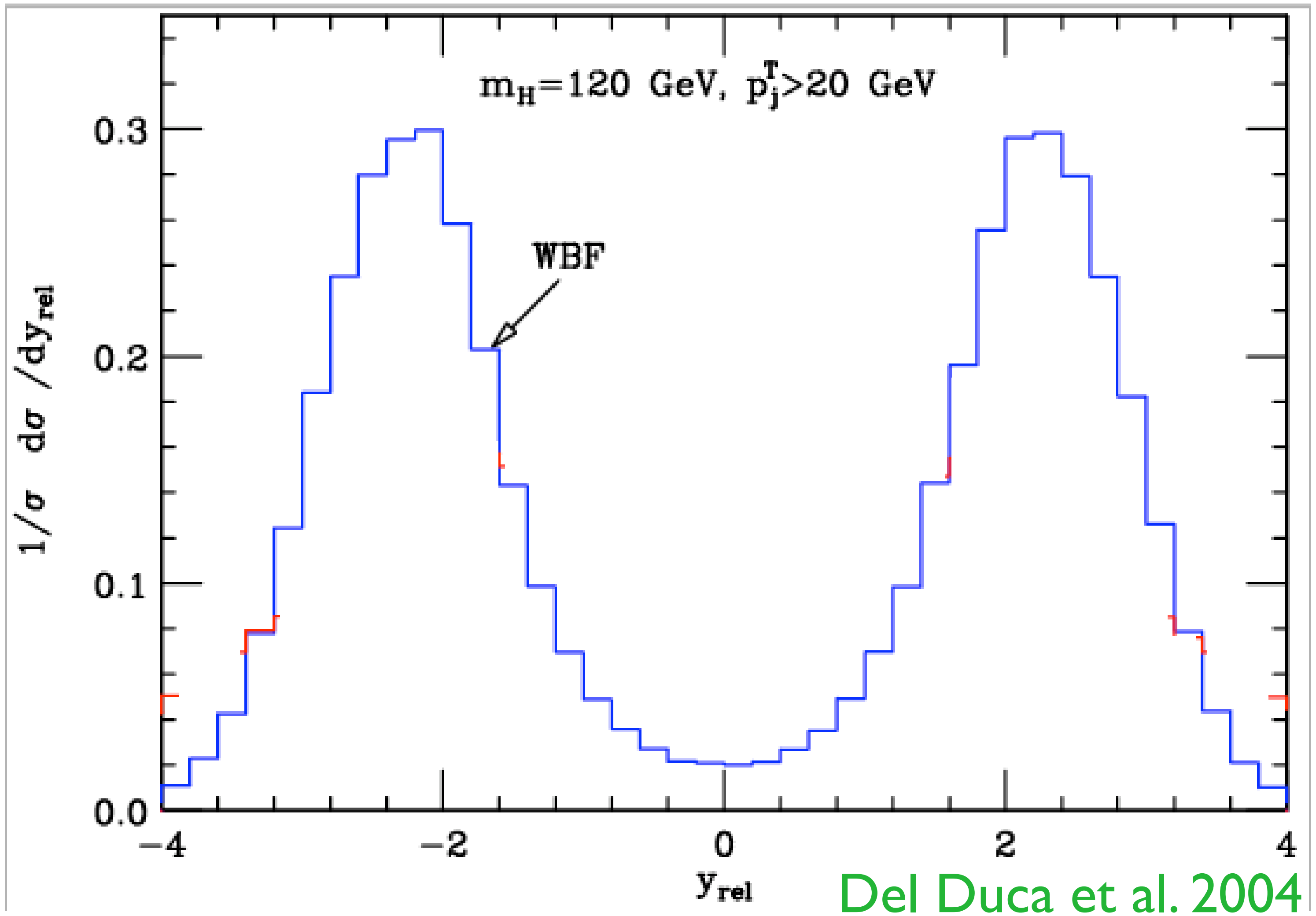
- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)

Couplings extraction from VBF

Vector boson fusion will play a crucial role in studying the Higgs properties, in many decay channels (ZZ,WW,ττ,ϒϒ). Typical signature is two forward jets and a “rapidity gap”. Central jet veto will be essential to select not only signal from background, but also VBF from QCD production.



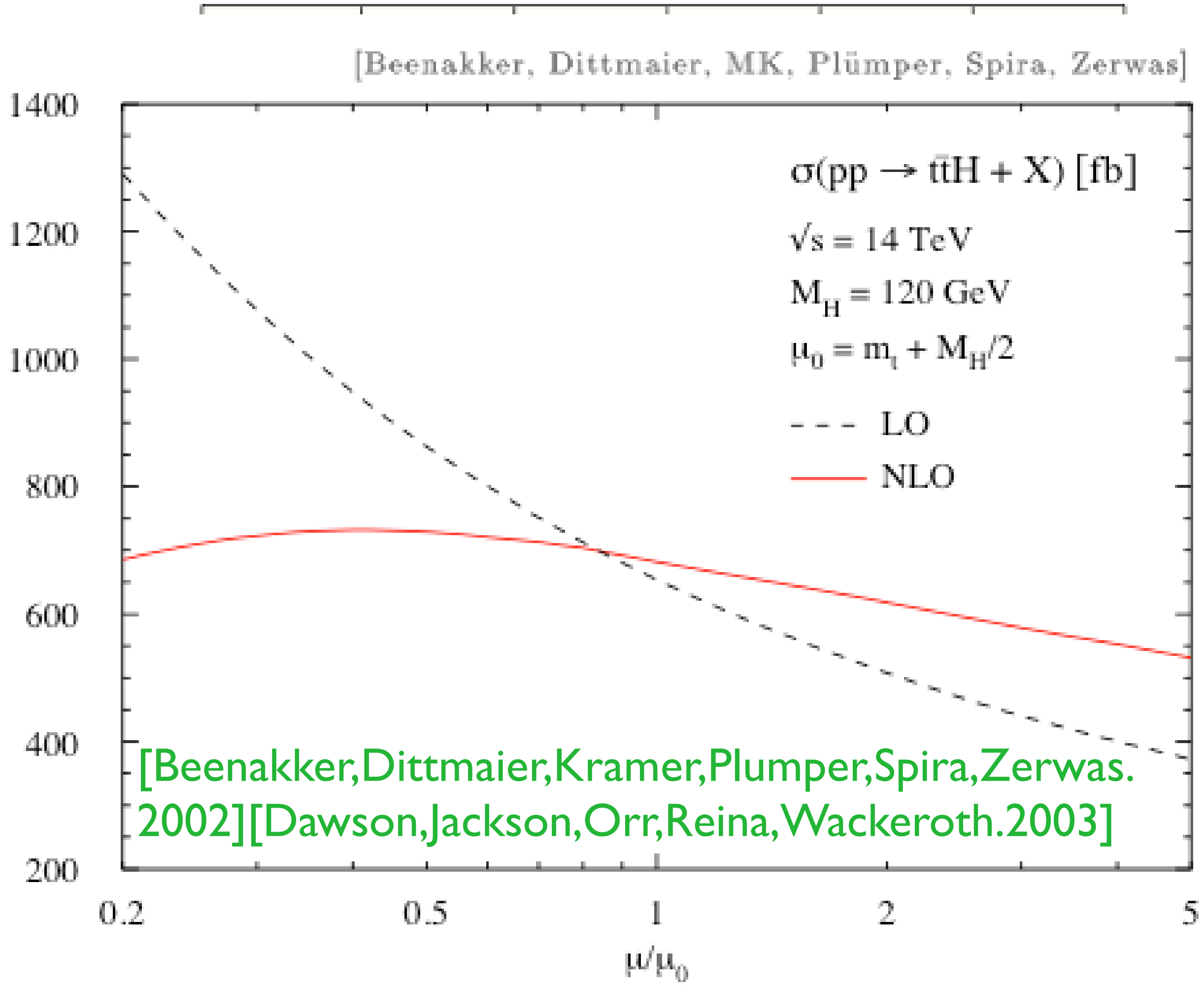




Del Duca et al. 2004

Central jet veto will be essential to select not only signal from background, but also VBF from QCD production. Matched description needed. Comparison with NLO results possible. Impact of minimum bias, underlying event, forward low-et jets difficult to predict ⇒ data modeling will be needed.

ttH production



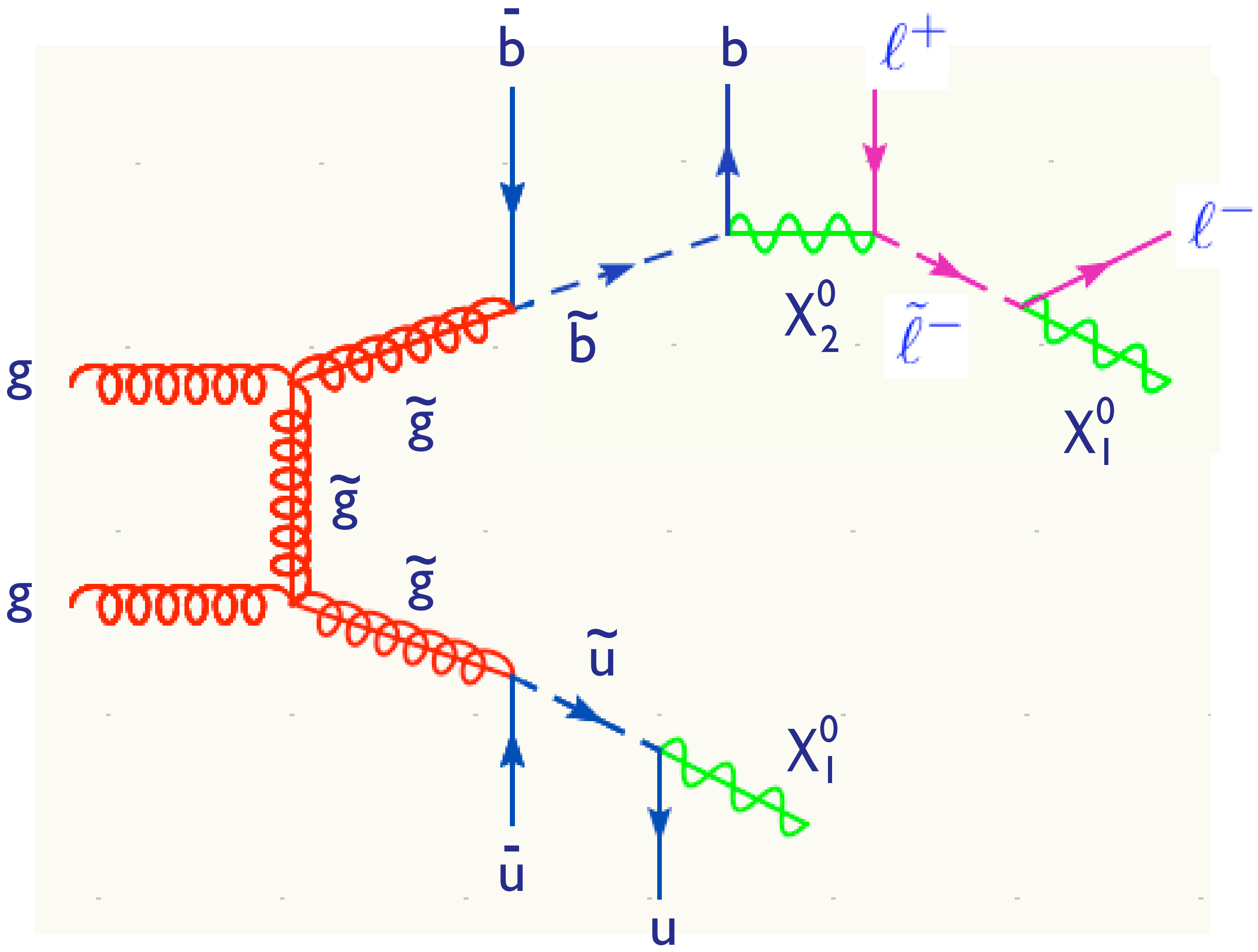
[Beenakker,Dittmaier,Kramer,Plumper,Spira,Zerwas. 2002][Dawson,Jackson,Orr,Reina,Wackeroth.2003]

Typical signature 4b+2j+l+mEt: very difficult!

Key issues:
1. Combinatorics
2. b-tagging
3. Invariant mass resolution
4. Background modeling: ttbb,ttjj are known only at LO⇒normalization very uncertain.

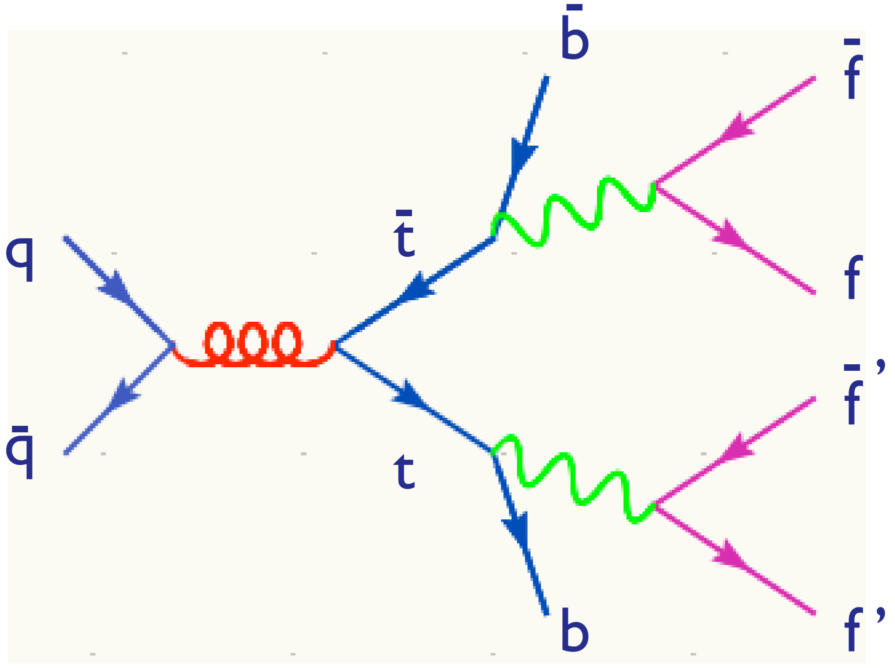
Extremely good knowledge of the detector necessary.

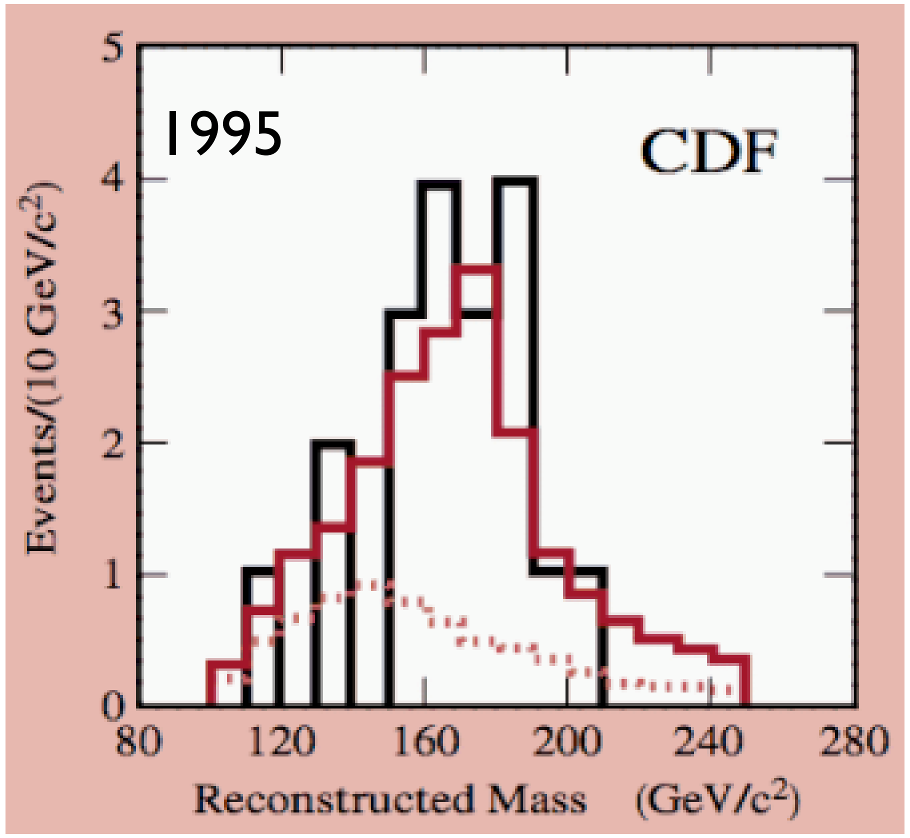
How are we going to discover BSM at the LHC?



Heavy states decaying in jets and leptons and $\not{E}_T$.

A lesson from the top





How did it go?

0. The only unknown was the top mass!

1. The experimentally easiest channel for triggering/ reconstruction/background-control was chosen.

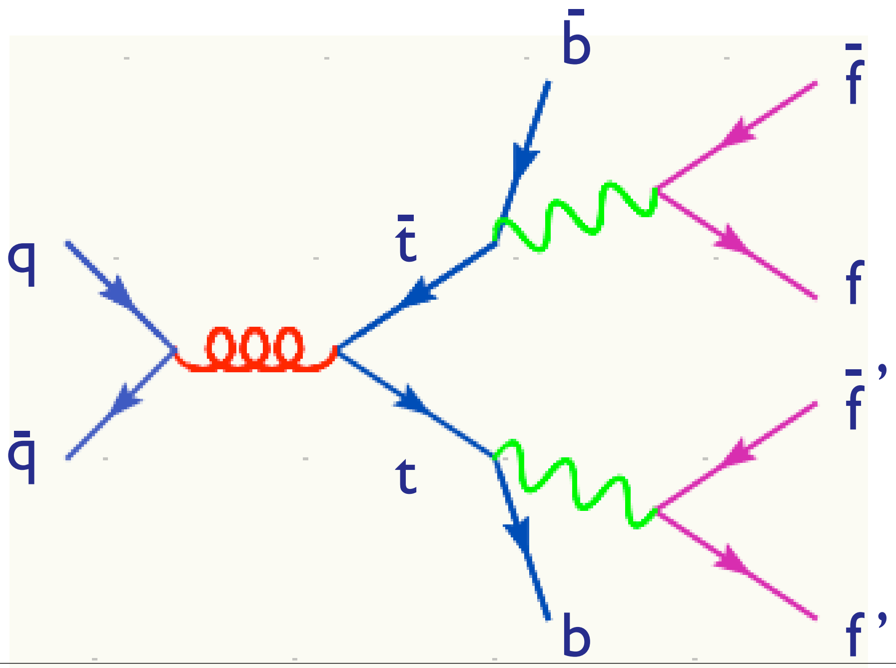
2. Mass reconstruction employed

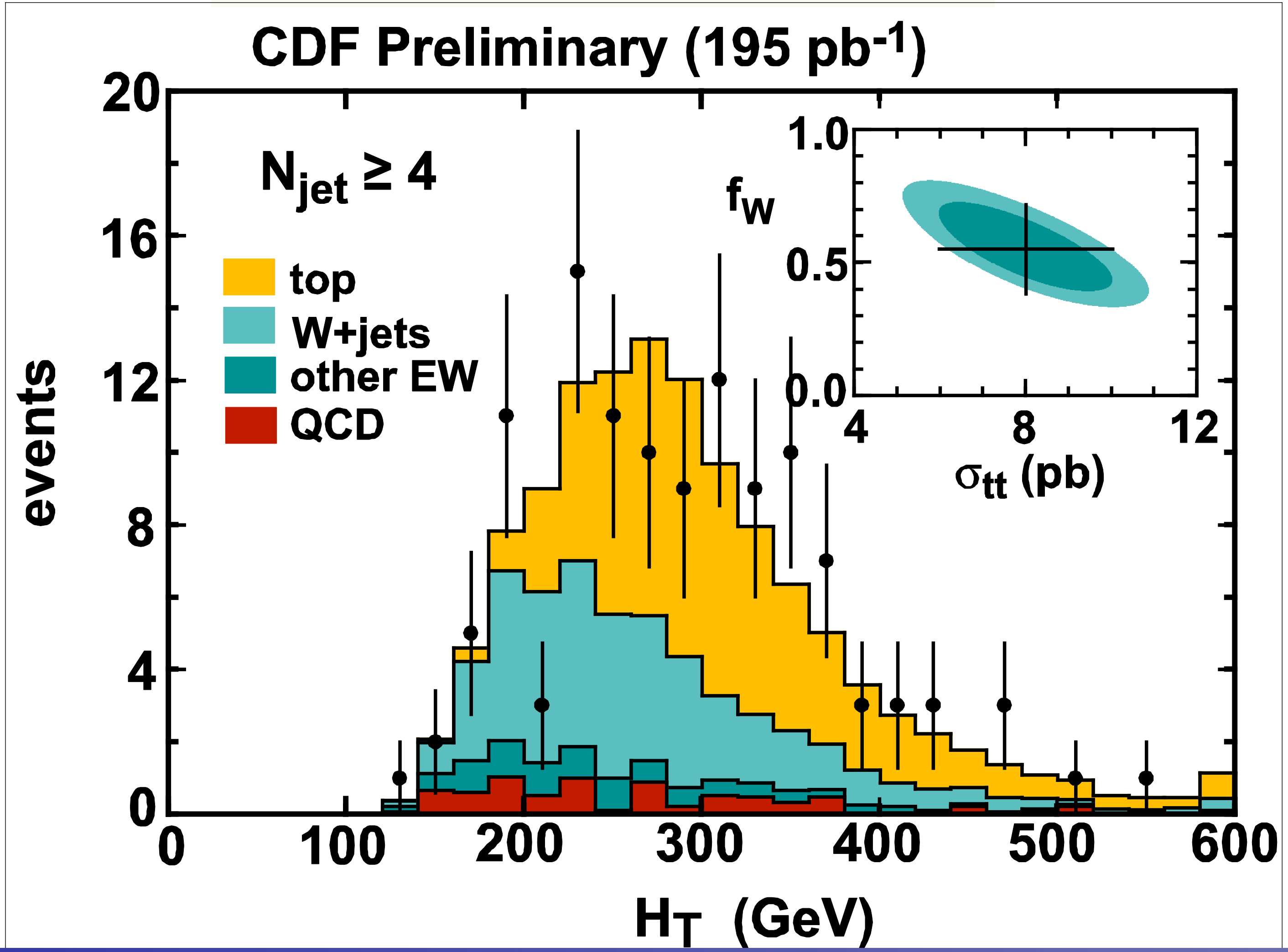
3. Backgrounds estimated via control samples with heavy flavors and also via MC ratio’s.

4. Number of events consistent with the cross section expectation from QCD

Handful of events was enough!

A lesson from the top





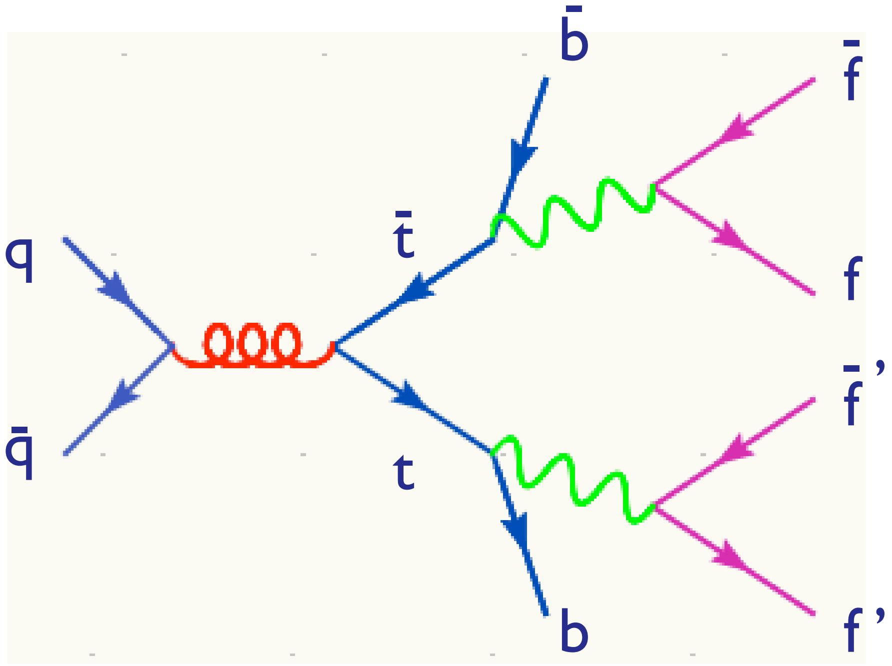
Immediately confirmed in Run II, also by the most inclusive measurements, H_T.

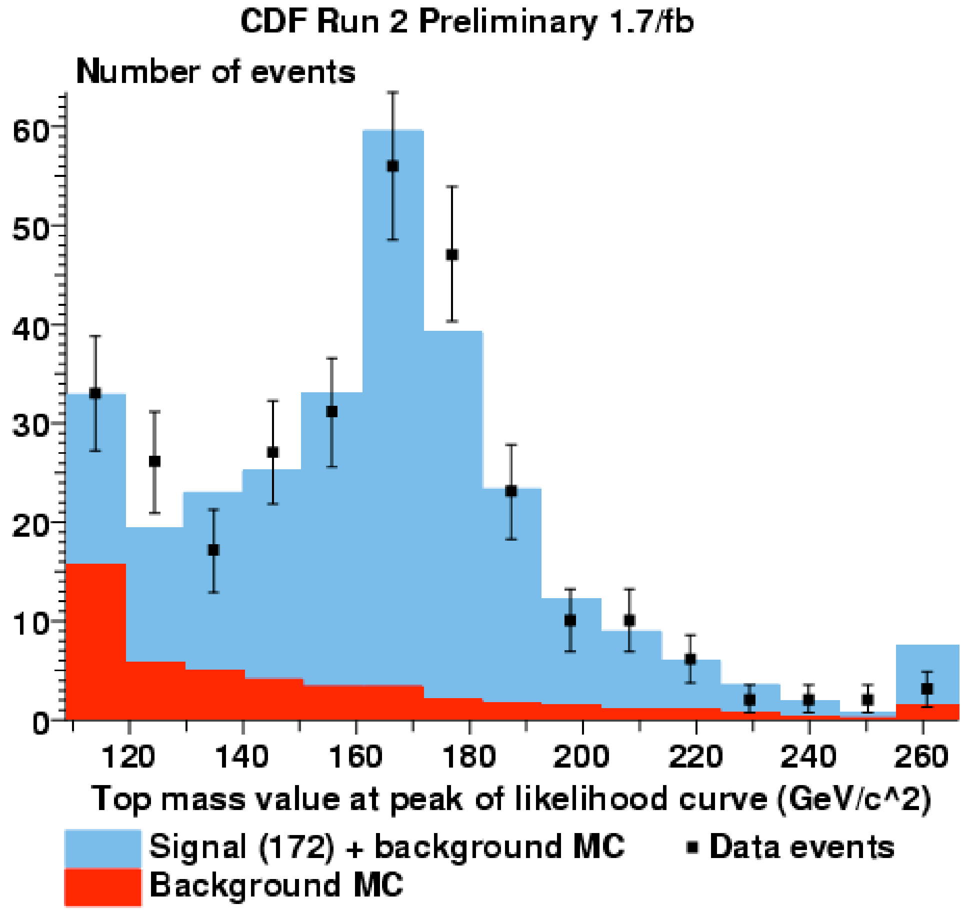
Other channels start to be considered as the statistics increases to have a consistent picture.

Cleaner and cleaner samples more exclusive studies:

1. W Polarization
2. BR’s ratio’s
3. Top Quark charge
4. Differential m_{tt} distribution
5. Search for new physics!!

A lesson from the top





Summary:

1. More than15-year long story

2. At all stages MC's played a role.

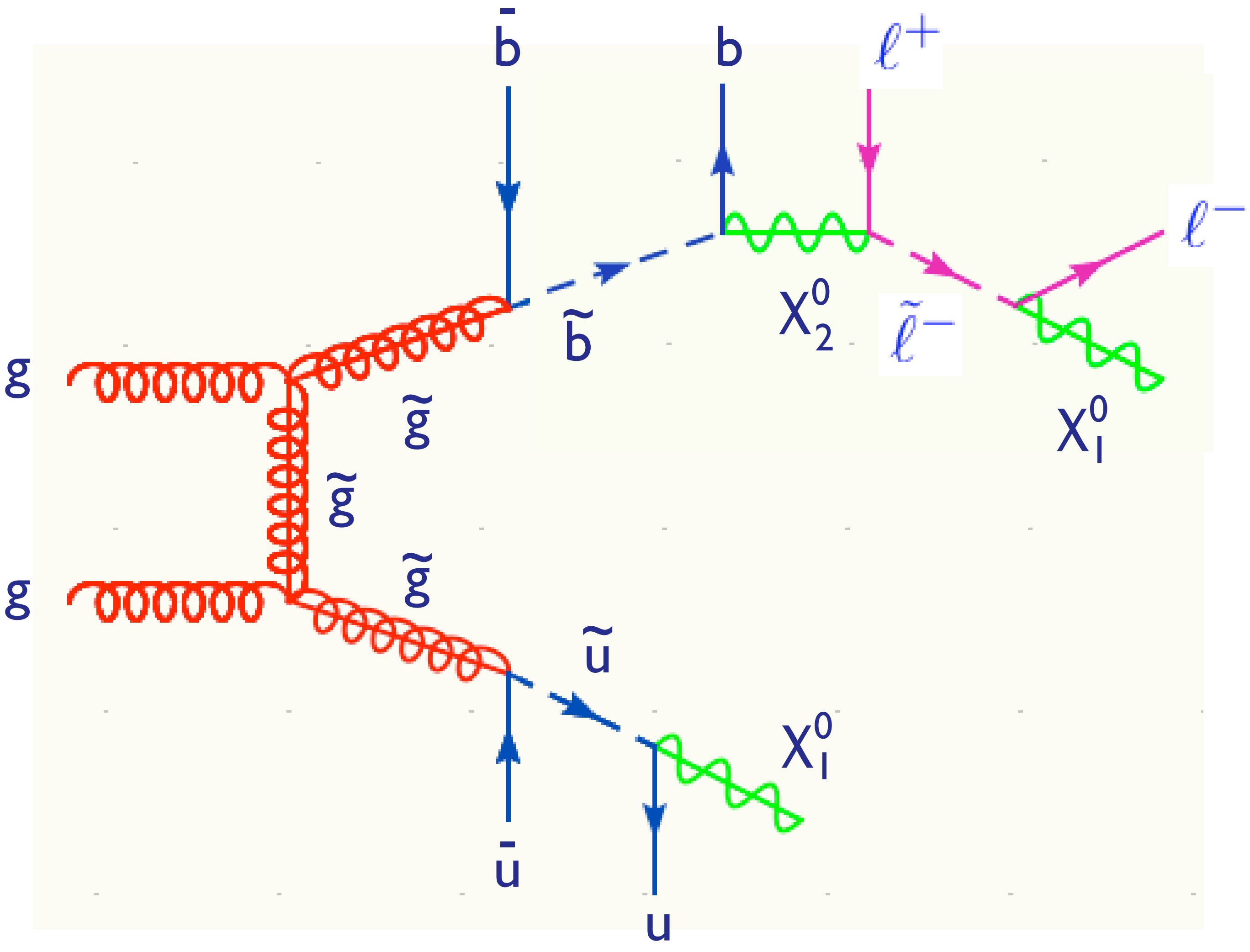
3. Now all studies, including the mass measurements, are strongly based on our simulation tools, i.e., matrix element methods.

More sophisticated analysis need more sophisticated MC's...

Is this strategy directly applicable to new heavy state searches?

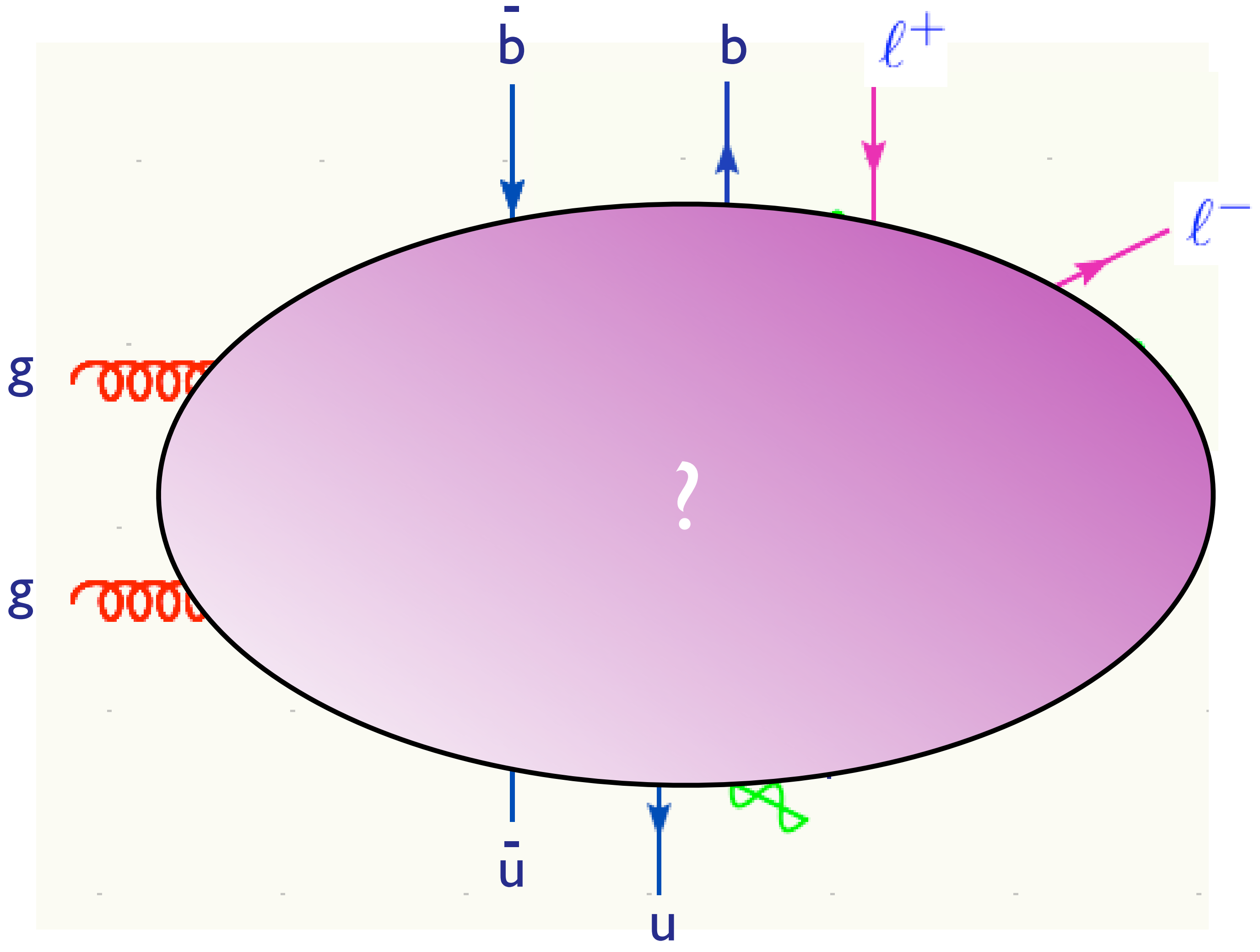
A lesson from the top

Susy inclusive searches are similar but more complicated final states.



A lesson from the top

Susy inclusive searches are similar but more complicated final states.

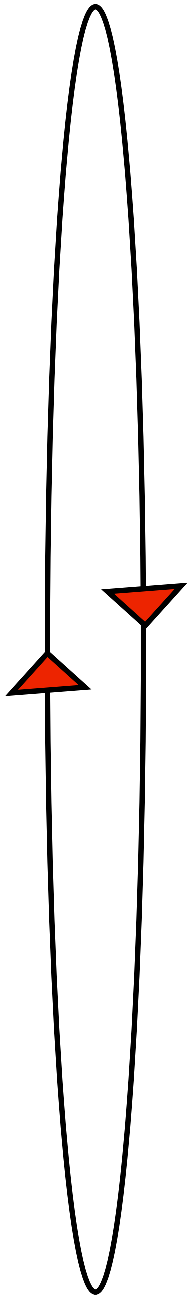


The main difference is that we don't know what to expect!!

Two approaches

- For new physics associated, two approaches are possible:
  - top-down (e.g. , model parameter scanning)
  - bottom-up (e.g., inverse problem, OSET)
- Different EXP strategies and different TH and MC tools:
  - Well defined models vs coarse structure
  - Extremely optimized (-> non portable) analyses vs general searches
  - Dedicated MC tools vs multipurpose MC's

The ambitious plan



1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t).
Flexible MC to be validated and tuned to control samples.
Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

2. Identify a finite set of coarse models compatible with the excess(es).

Inverse problem tools (Ex: OSET)

3. Look for "predicted excesses" in other channels.

Simulation of any BSM signature: from models to events in an easy and fast way.

4. Refine

Accurate predictions for cross sections of selected models (Ex: SUSY) to identify couplings.
Accurate predictions for primary couplings (Ex: spectra calculators).

5. Perform more detailed studies to measure mass spectrum, quantum numbers, couplings.

Accurate ME based description for final state distributions which keeps all the relevant information (Ex. decay chain with spin).

6. Refine

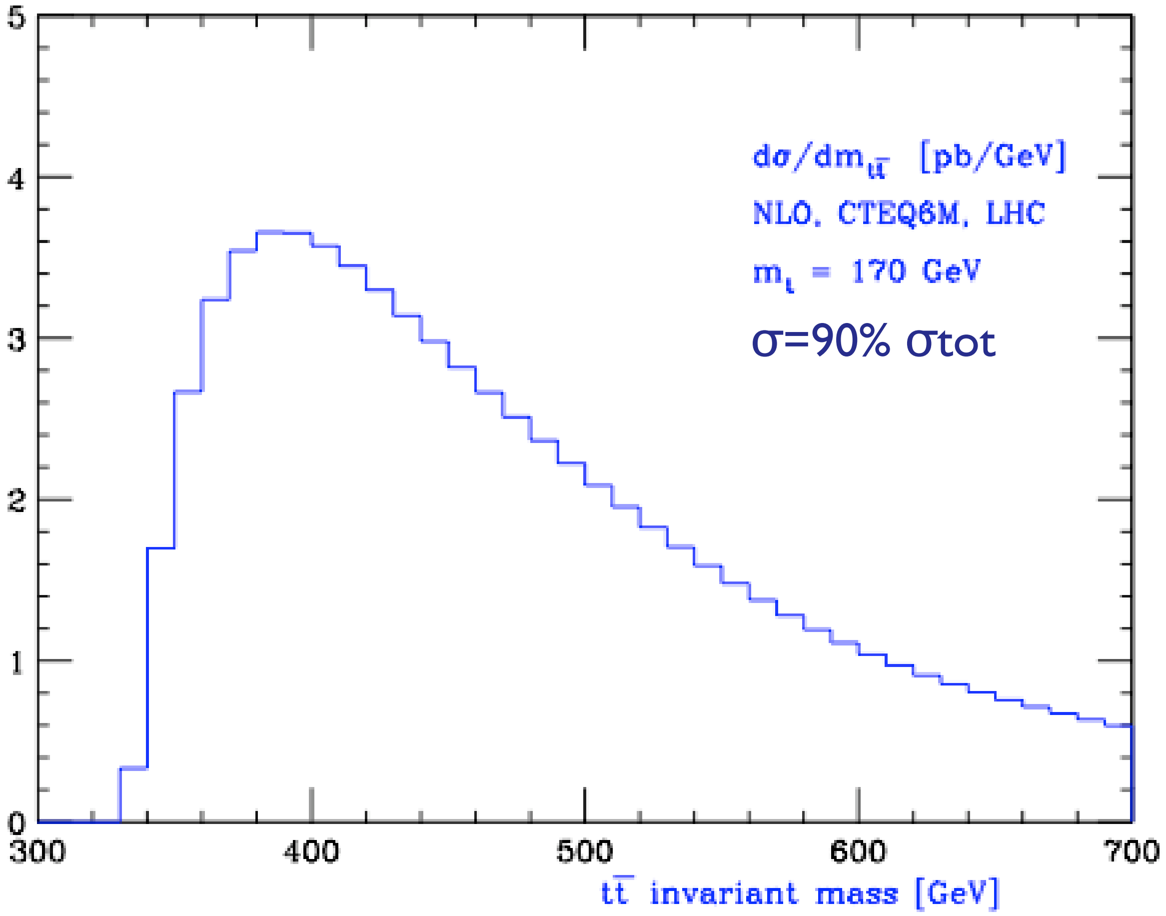
Off-shell effects, Matrix Element methods, Global fits (Ex: Sfitter)

A more modest bottom-up strategy

1. Focus on a specific SM observable that is
    a. naturally sensitive to BSM
    b. is well-predicted & possibly "background free"
2. Search for a simple signature, eg "a peak" in a "model independent" way.
3. Information vs luminosity plan.

Example: m_{tt} spectrum

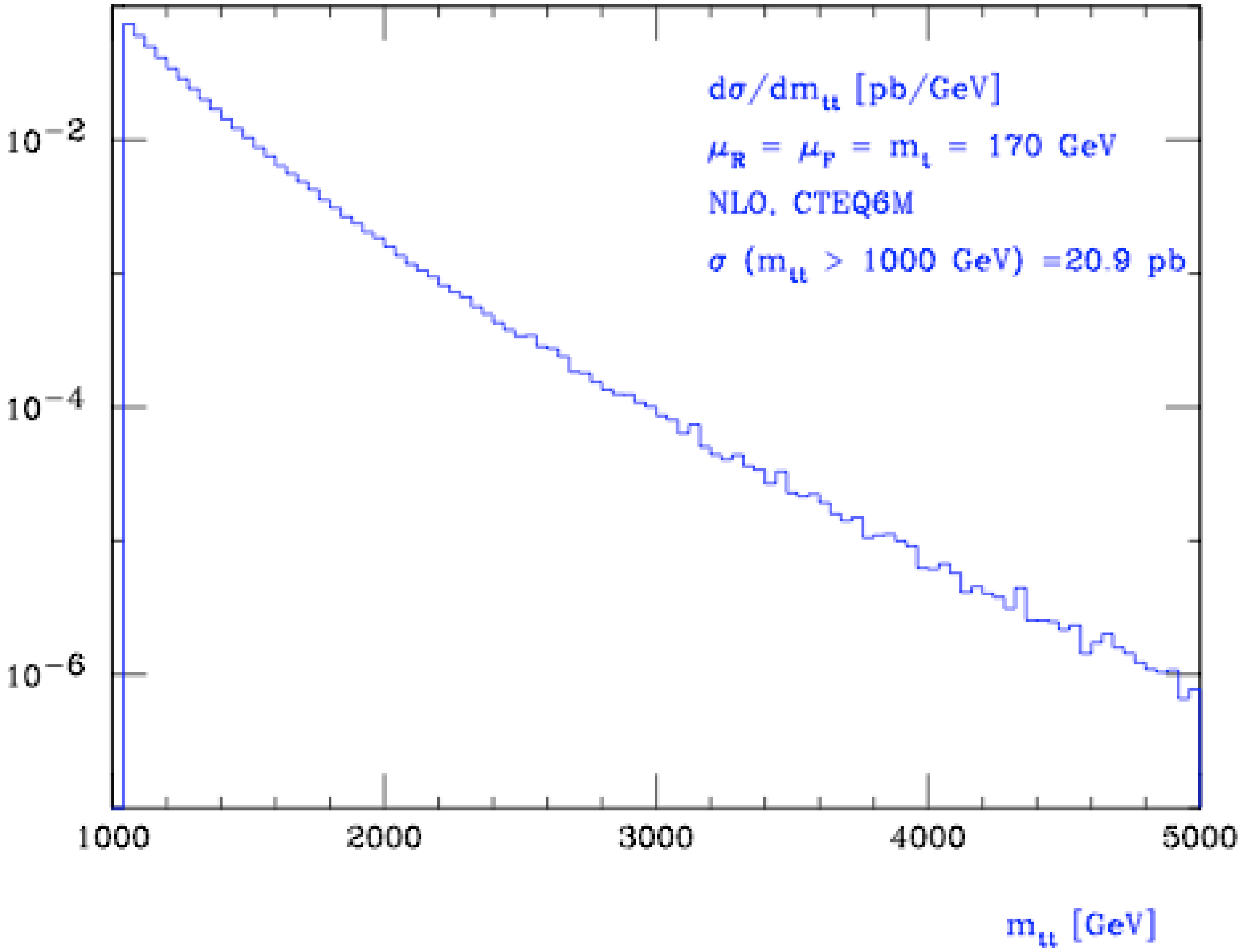
low invariant mass



* ~90% of the total cross section
* ttbar at threshold in a 1S0[tt] state
* High-statistics sample⇒

  - early SM physics
  - CP-violation
  - top rare decays
  - low mass new resonances

high invariant mass



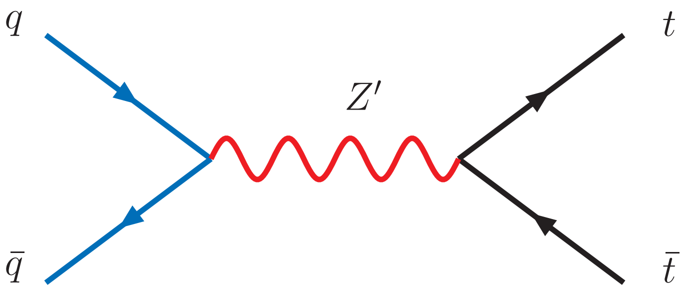
* m_{tt} >1 TeV ⇒ ~2% of the total cross section

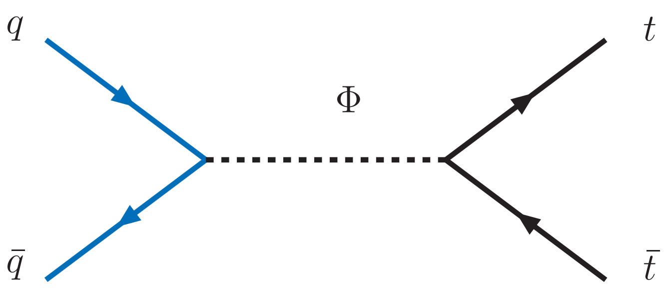
* Events are more 2jet like ⇒ different selection

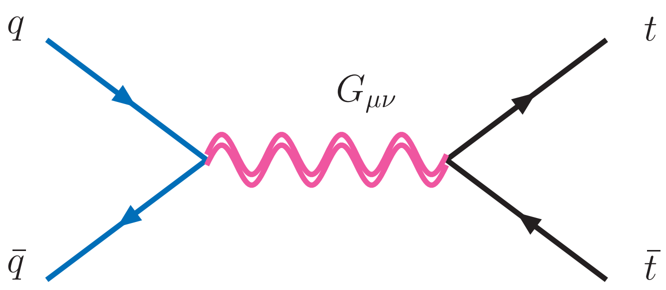
* EW effects (e.g. P-violation) start to be important
* Relevance of qq+qg increases
* TeV Resonances searches
* Top partners searches

New resonances

In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.



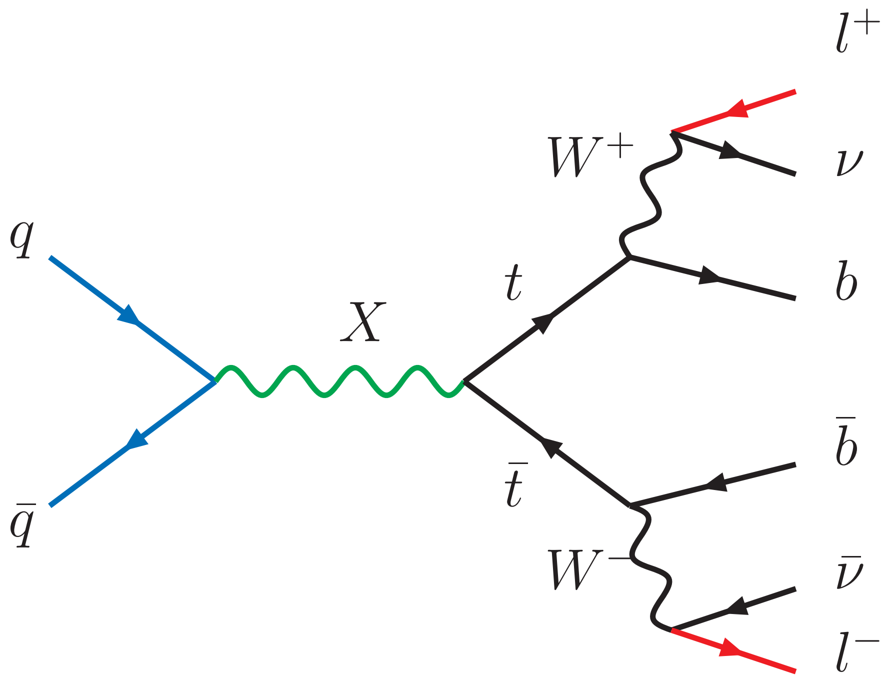




Given the large number of models, in this case is more efficient to adopt a "model independent" search and try to get as much information as possible on the quantum numbers and coupling of the resonance.

To access the spin of the intermediate resonance spin correlations should be measured.

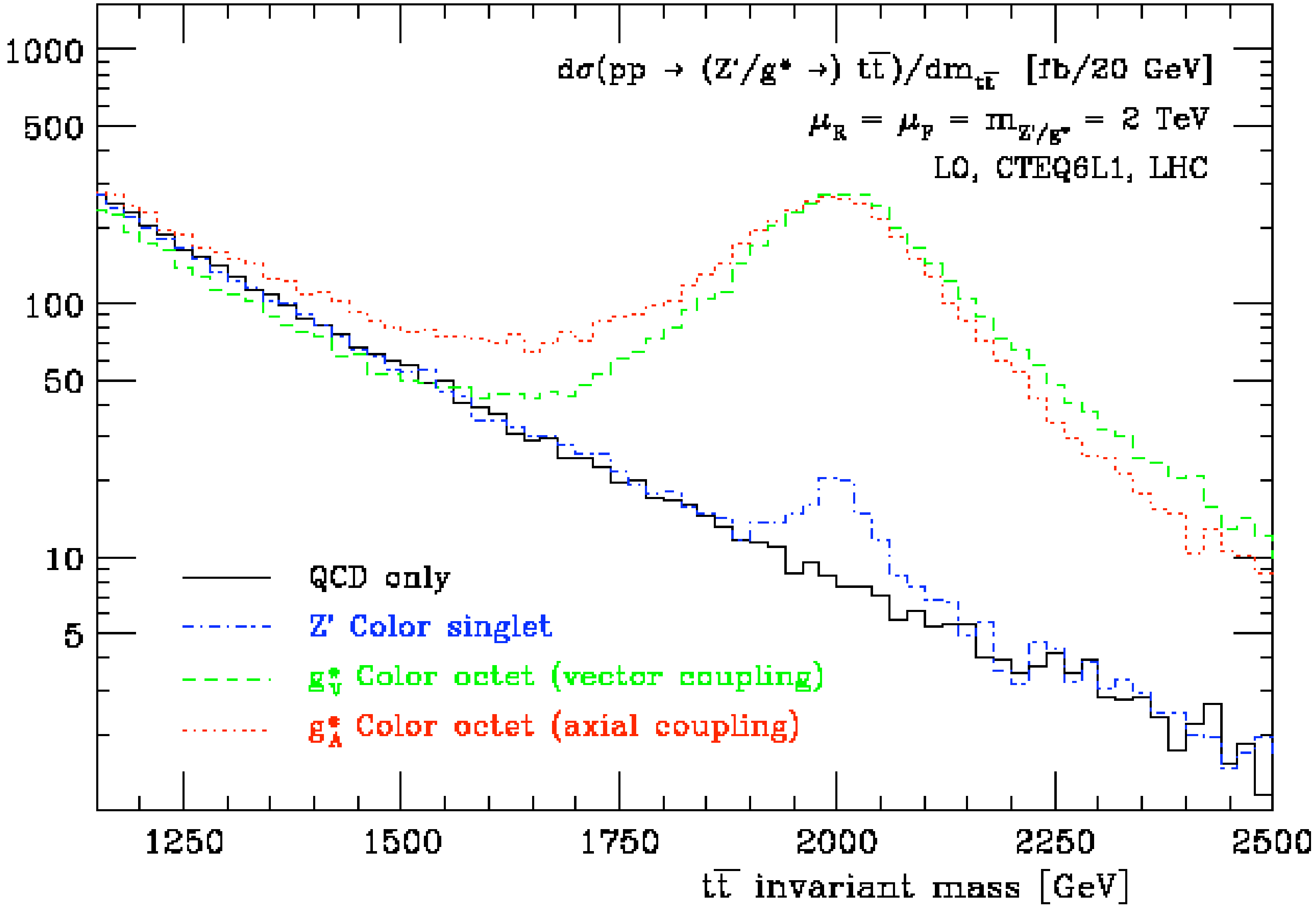
It therefore mandatory for such cases to have MC samples where spin correlations are kept and the full matrix element pp>X>tt>6f is used.



Zoology of new resonances

Spin	Color	$(1,\gamma_5)$ [L,R]	SM-interf	Example
0	0	(1,0)	no	Scalar
	0	(0,1)	no	PseudoScalar
	0	(0,1)	yes	Boso-phobic
	8	(0,1),(1,0)	no	Techni-pi0[8]
1	0	[sm,sm]	yes/no	Z’
	0	(1,0),(0,1)(1,1),(1,-1)	yes	vector
	8	(1,0)	yes	coloron/kk-gluon
	8	(0,1)	“yes”	axigluon
2	0	--	yes	kk-graviton

Phase I: discovery



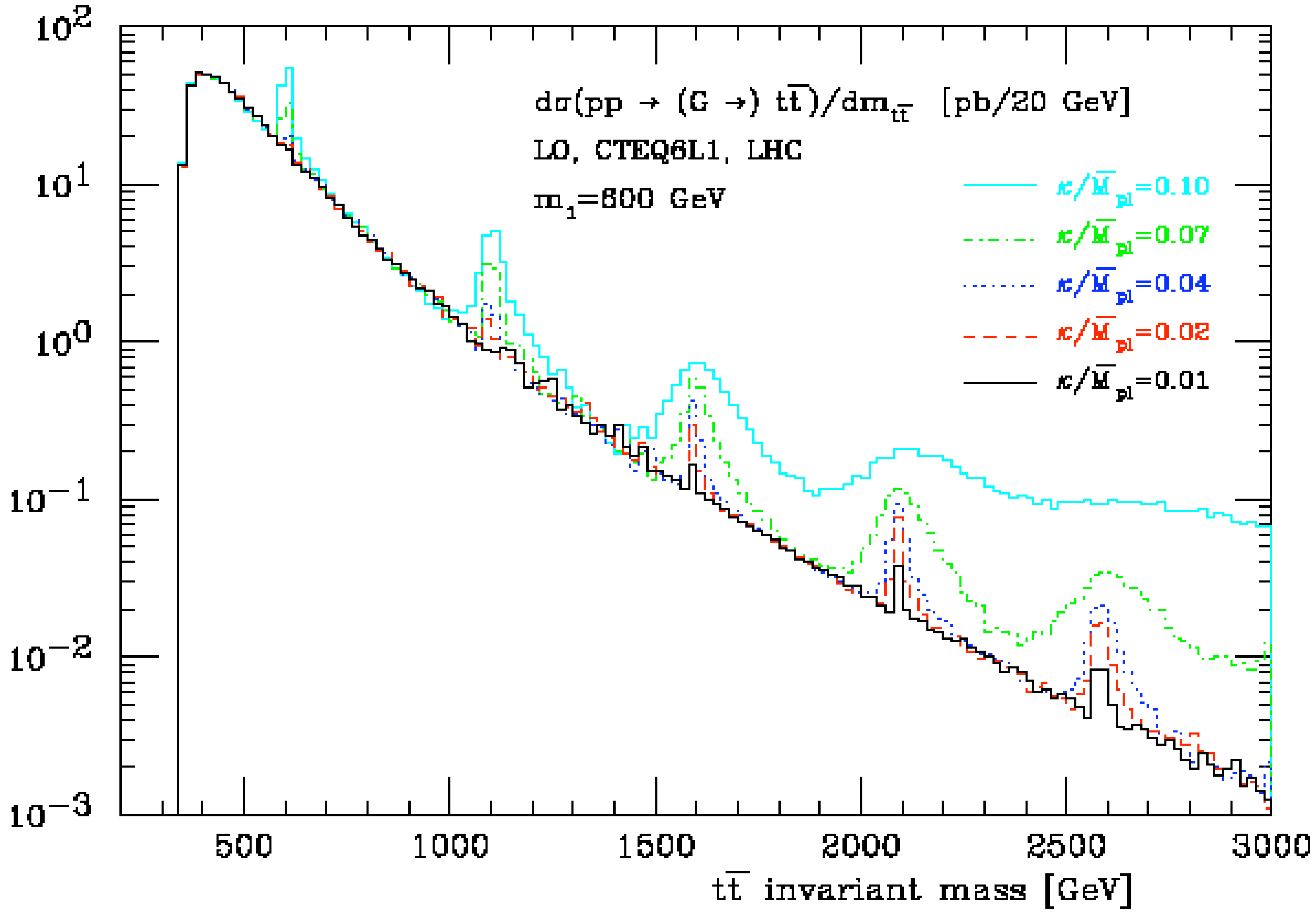
*Vector resonance, in a color singlet or octet states.

*Widths and rates very different

* Interference effects with SM ttbar production not always negligible

* Direct information on σ•Br and Γ.

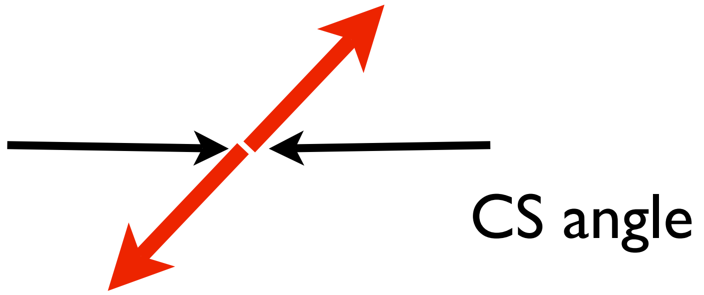
Phase 1: discovery

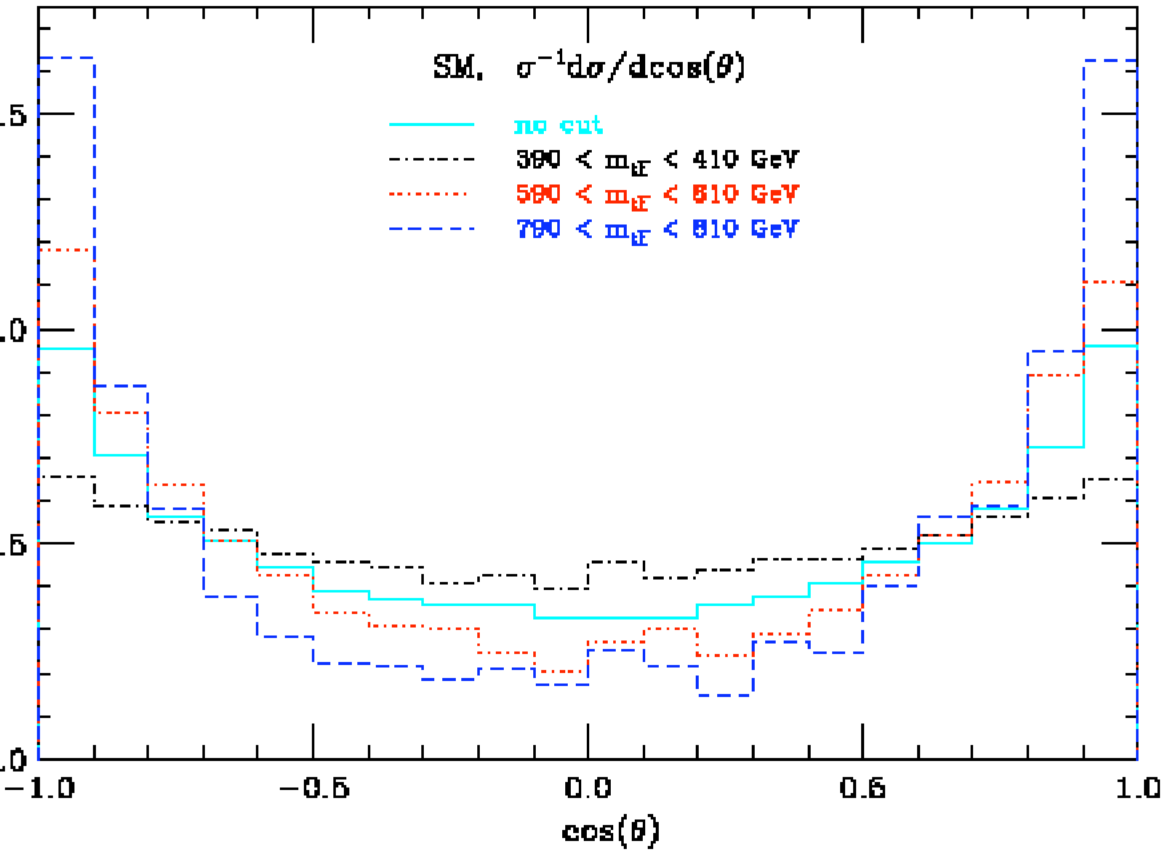


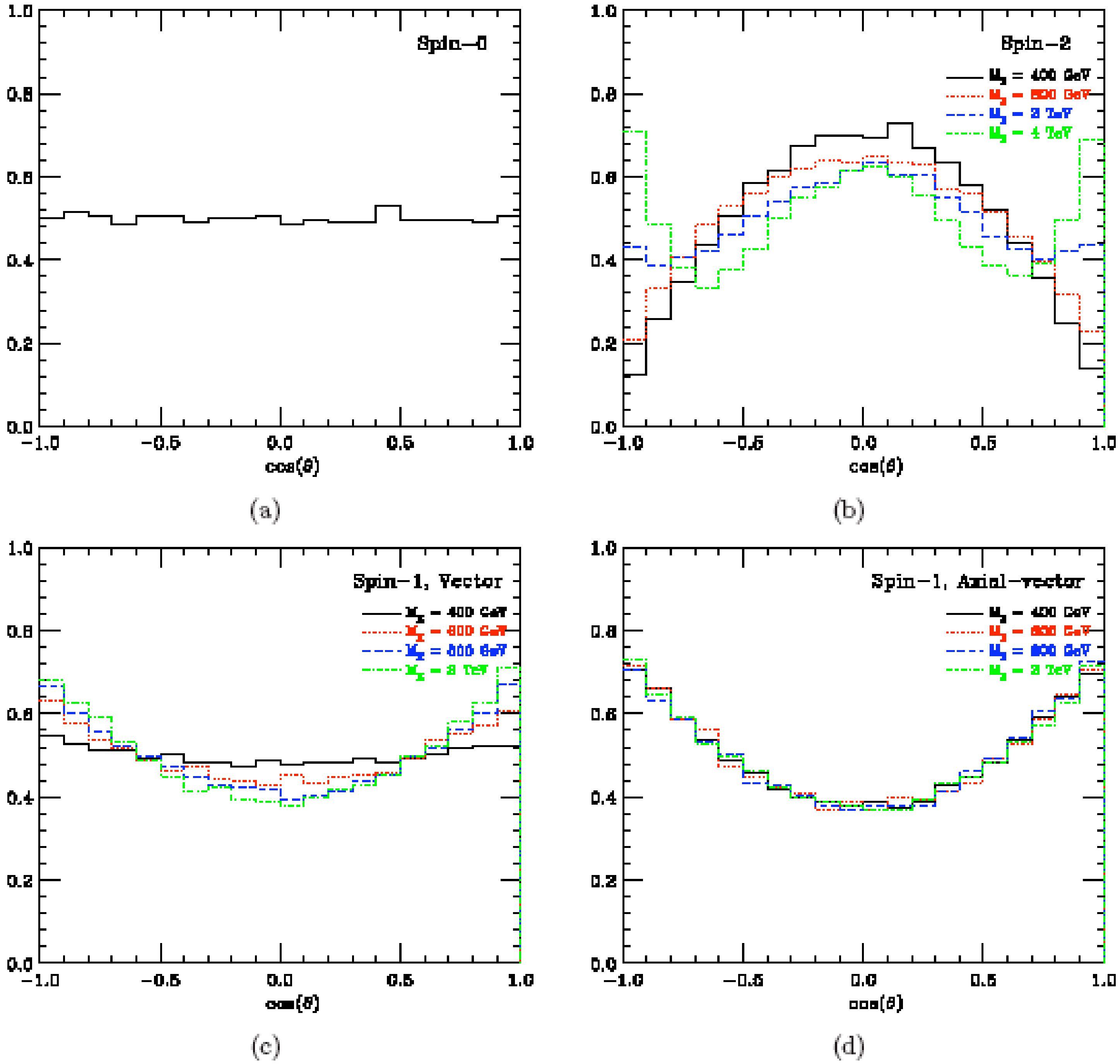
* Spectacular signature!

*RS Model with first KK=600 GeV

Phase 2: ttbar angular distributions





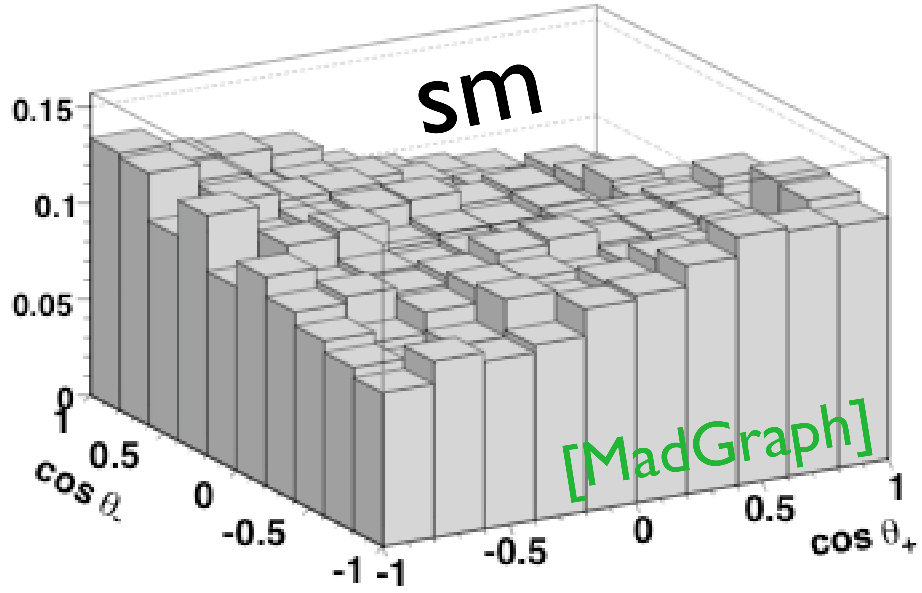


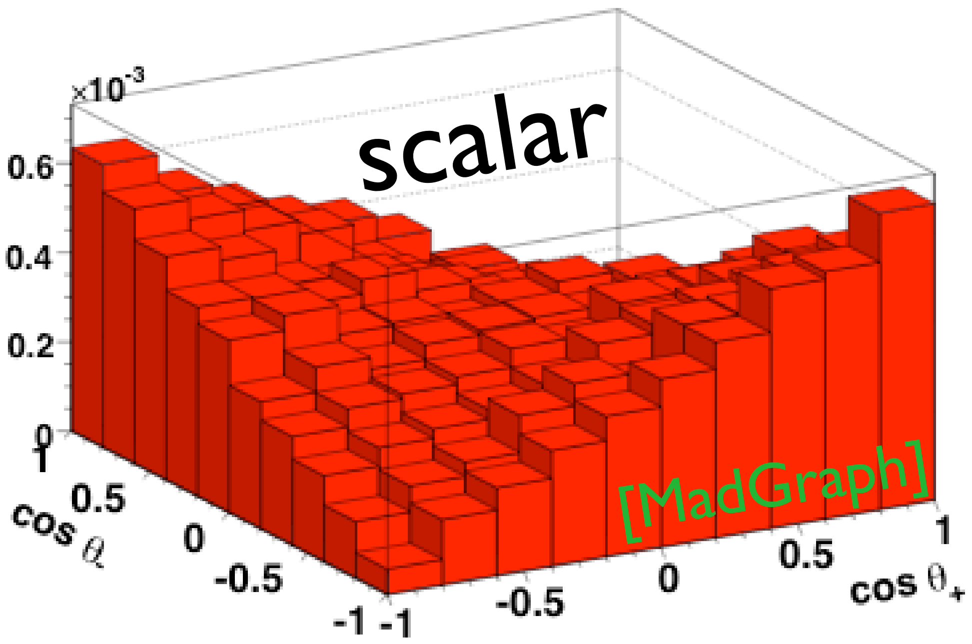
(a) (b)

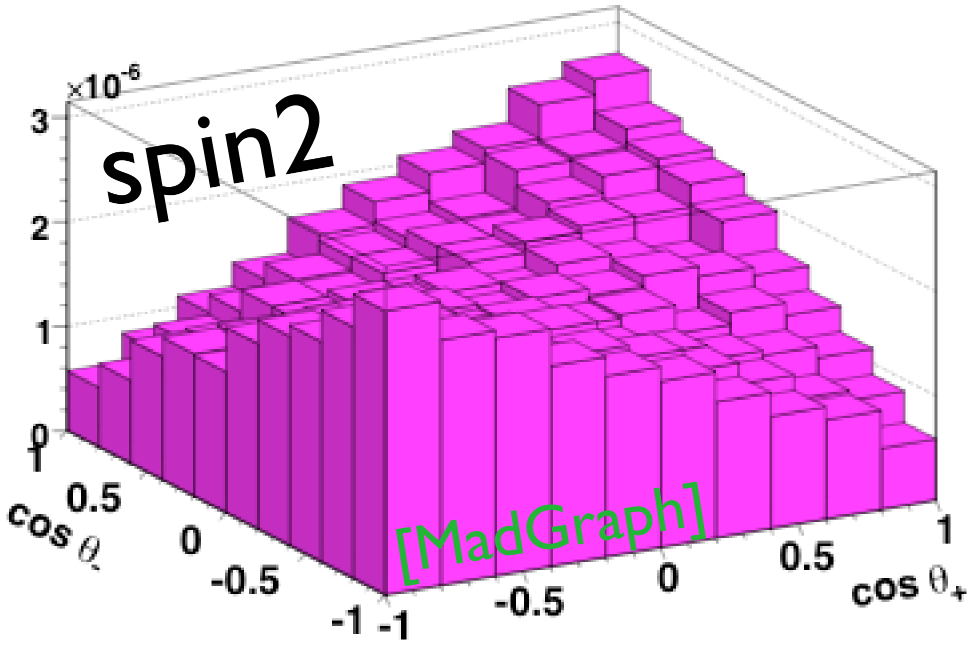
(c) (d)

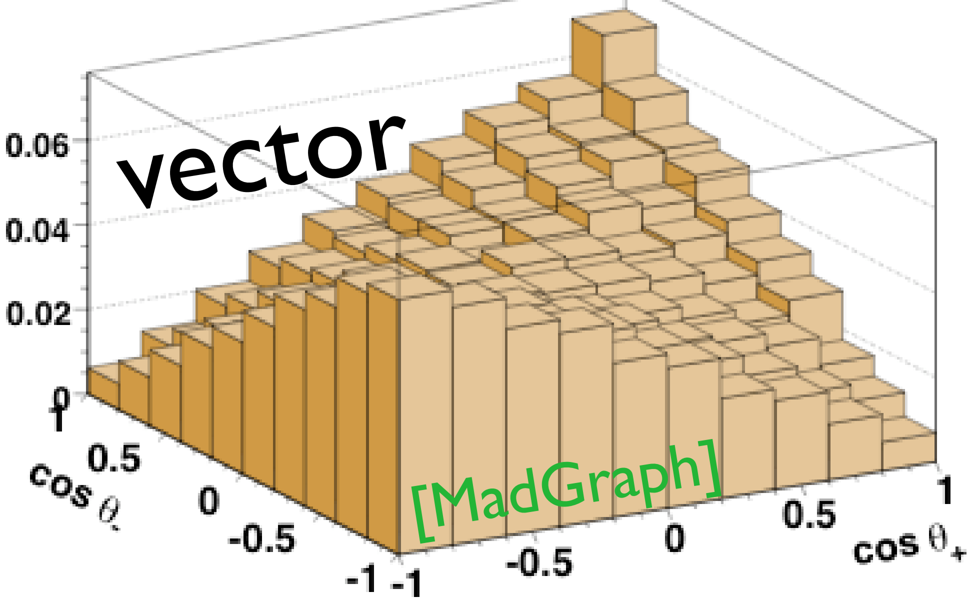
Robust reconstruction needed, but much easier than spin correlations...

Phase 3: Spin correlations







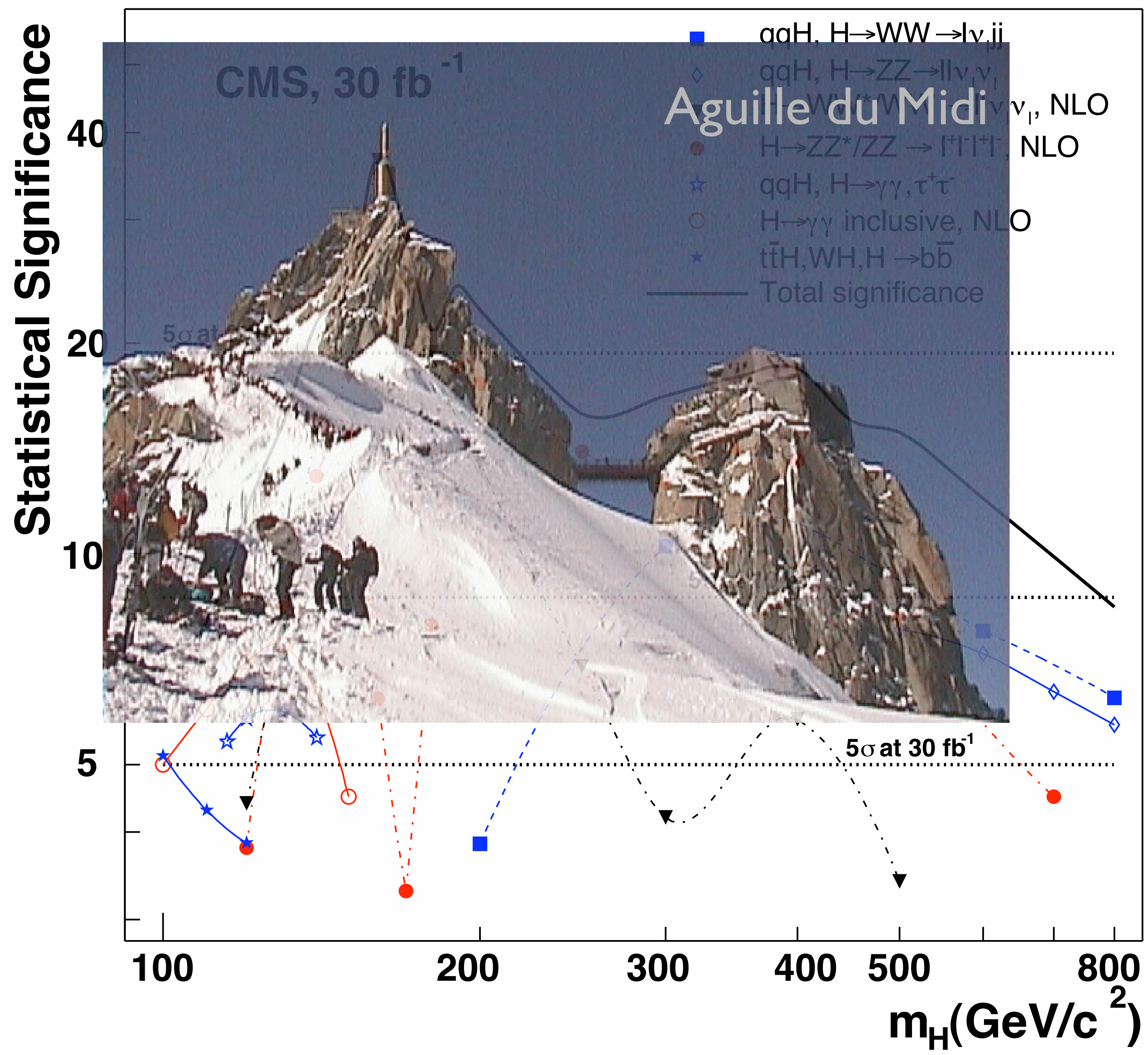


Summary

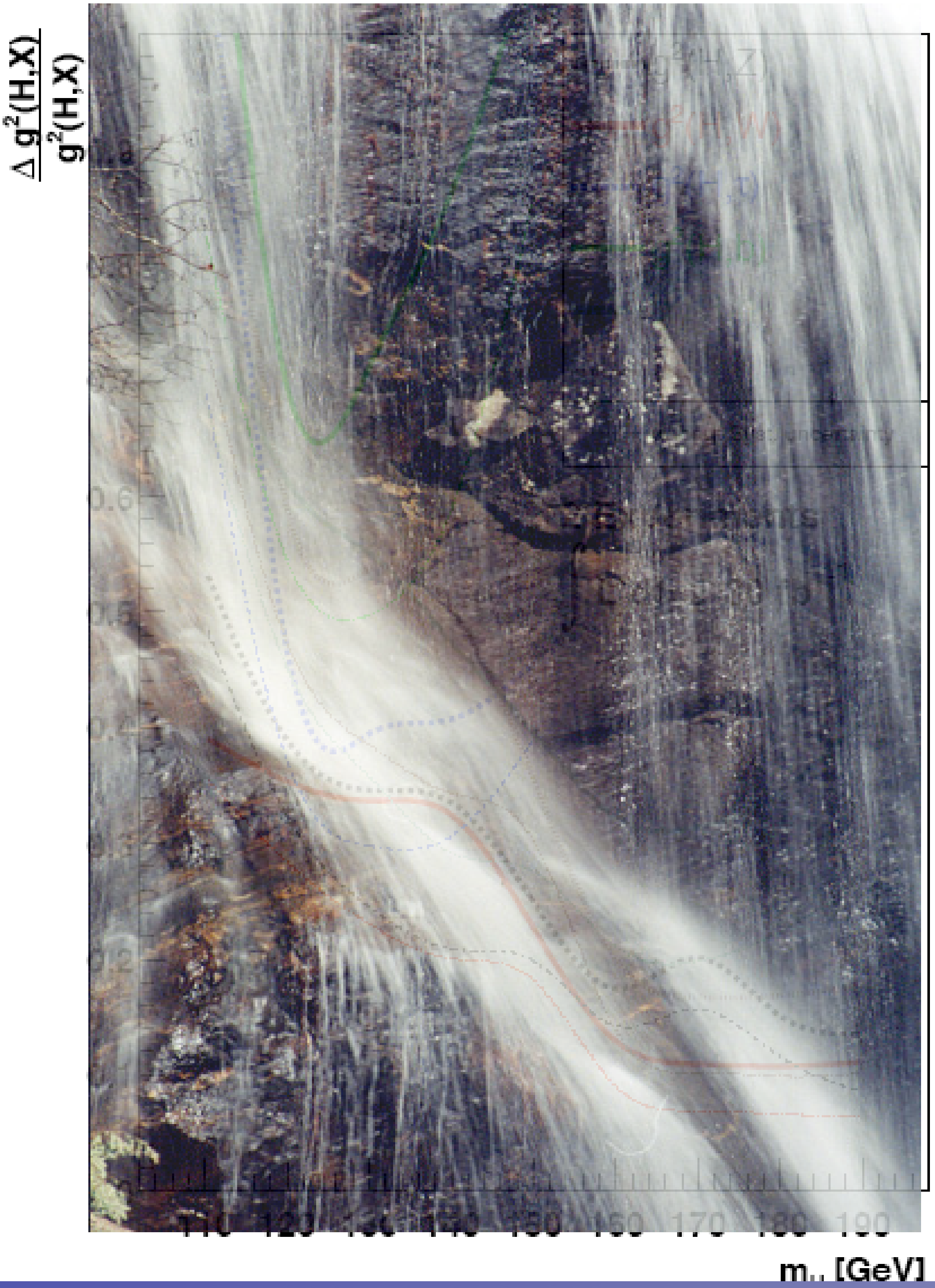
- The Standard Model of EW interactions provides an excellent description of exp data and predicts the Higgs boson.
- Several EXP and TH arguments lead us to believe (and hope) that there might be something radically new at a scale of 1 TeV.
- We are entering now one of the most exciting times for particle physics, better to keep our eyes wide open...

... and never forget to unleash your imagination!

SM Higgs discovery reach



Accuracy on SM Higgs couplings at the LHC



Higgs bounds from Tevatron (2006)