Conclusiones Teóricas

Germán Rodrigo

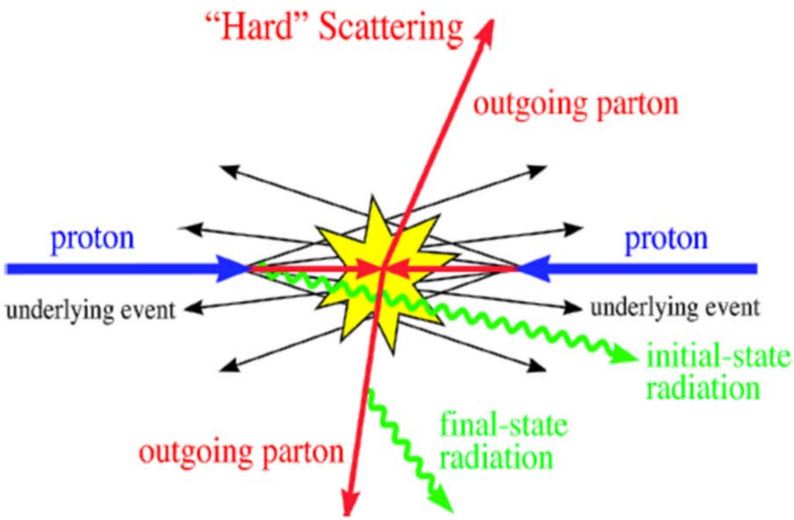
III Jornadas CPAN, Barcelona 2-4 Nov 2011

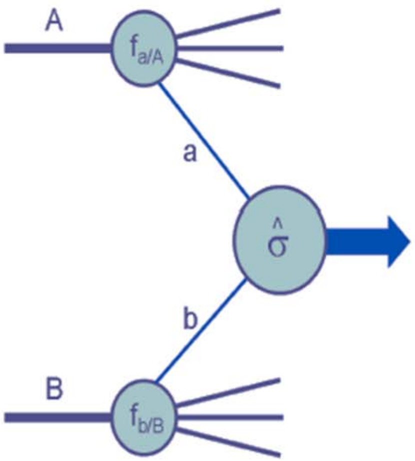
Outline

- Theoretical predictions at hadron colliders
- The NLO revolution
- Theoretical tools
- Jetography
- Tevatron anomalies: top quark charge asymmetry and W+2jets, and the LHC

Factorization in hadronic collisions

Factorize physics into **long distance** (hadronic ~ M_{had}), and **short distance** (partonic $Q \gg M_{\mathrm{had}}$), factorization violation is power supressed ~$\mathcal{O}\left(M_{\mathrm{had}}/Q\right)^q$





Parton densities PDF

Hard scattering cross-section

$$\sigma = \sum_{a,b} \int dx_1\, dx_2\, f_a(x_1,\mu_F)\, f_b(x_2,\mu_F)\, \hat{\sigma}_{ab}(x_1 p_A, x_2 p_B; \mu_F, \mu_R) + \mathcal{O}\left(\frac{1}{Q}\right)$$

Factorization and renormalization scales

Higher twist

Parton distribution functions

- Non-perturb. input determined from global fits to collider data, scale evolution from pQCD (NNLO)
- Vast choice

MSTW	Martin, Stirling Thorne, Watt
CTEQ/CT	Pumplin, Huston, Lai, Li, Nadolsky, Tung, Yuang
GJR	Gluck, Jiménez-Delgado, Reya
NNPDF	Ball, del Debbio, Forte, Guffanti, Latorre, Rojo, Ubiali
ABKM	Alekhin, Blümlein, Klein, Moch
HERAPDF	Aaron et al.

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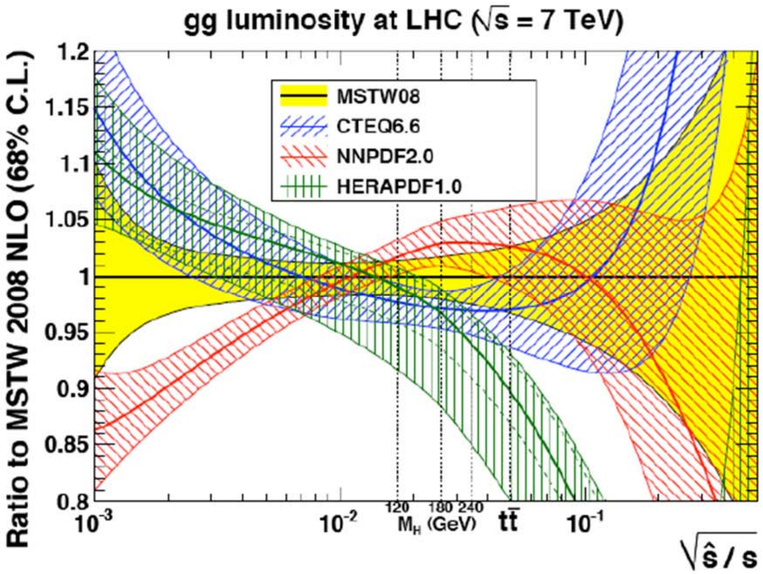

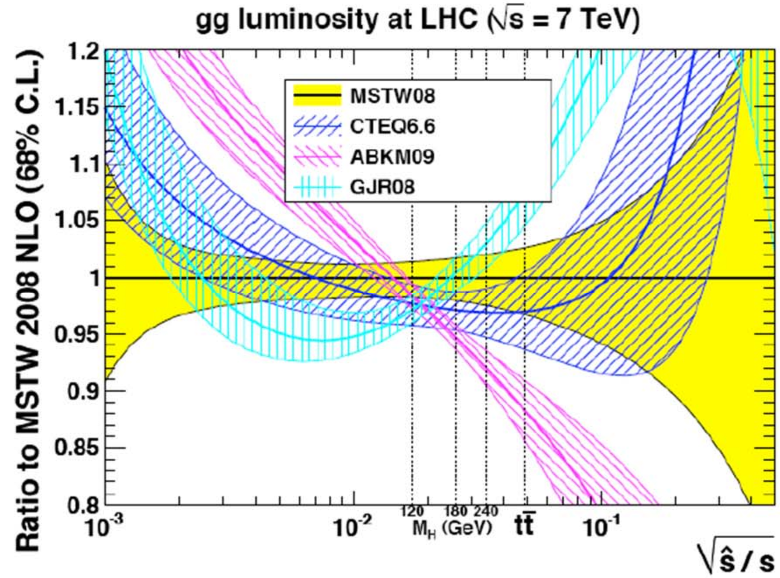

- Differences are due to different:

Data sets in fits, parameterization of starting distributions, order of pQCD evolution, power law contributions, nuclear target corrections, resummation corrections (ln 1/x, …), treatment of heavy quarks, strong coupling, choice of factorization and renormalization scales.

- at least 5-10% uncertainty in theoretical predictions

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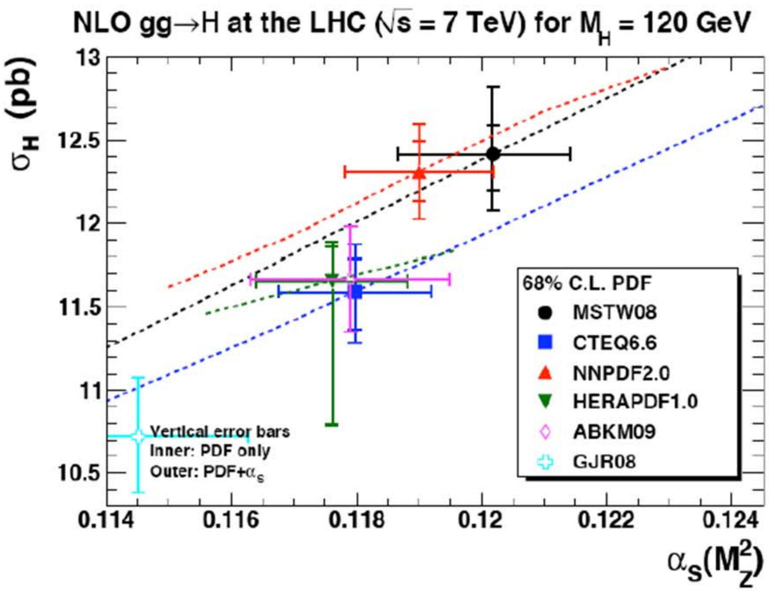

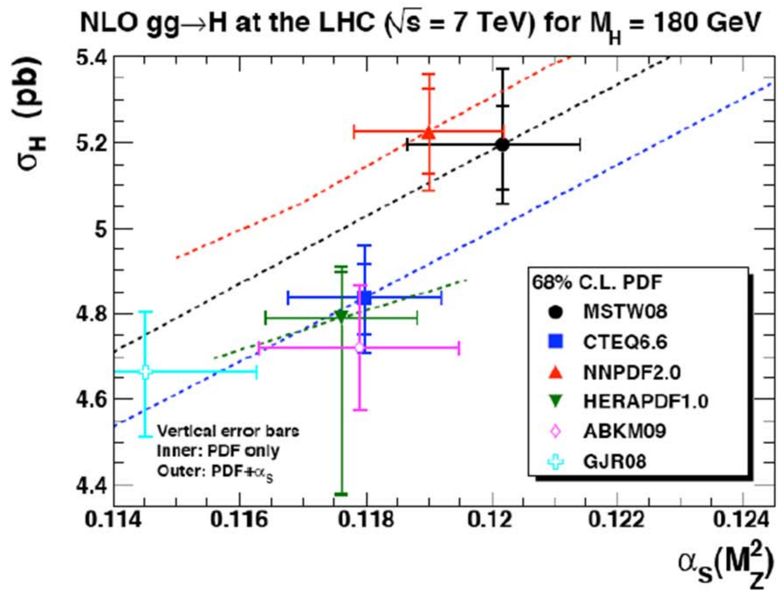

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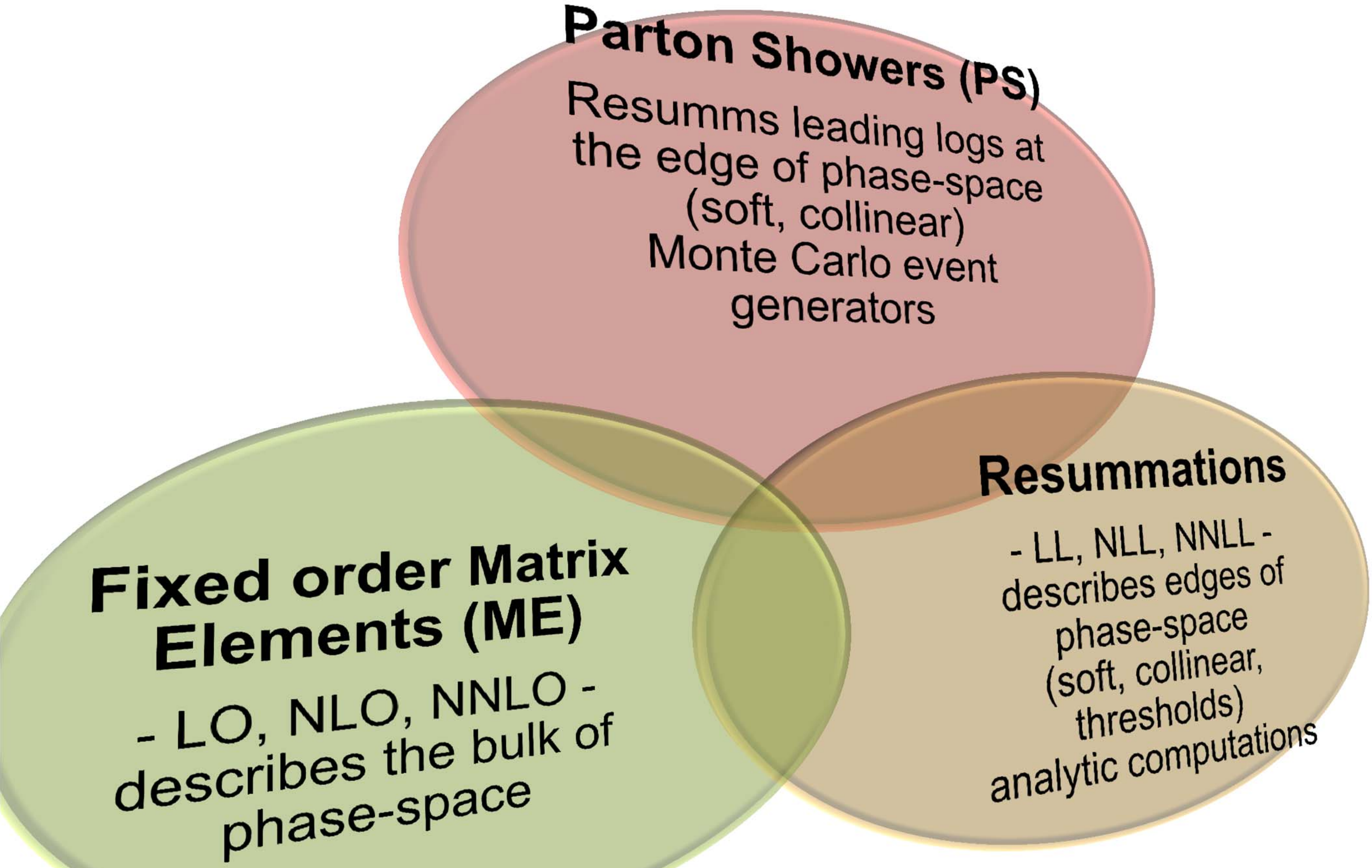
Hard scattering

- thanks to asymptotic freedom can be computed in pQCD



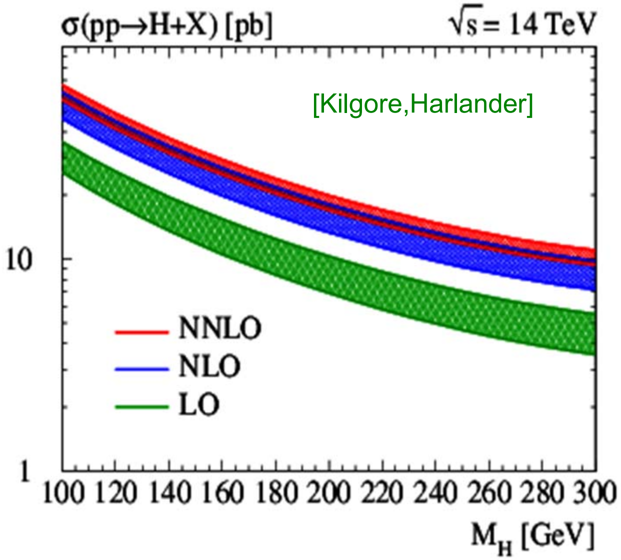
ME: why many legs ?

The LHC is a hadronic machine working at higher energies than ever before

- larger phase-space for hard radiation
- higher multiplicities (external legs): more powers of α_S
- proton is not elementary: new channels might open at higher orders
- huge soft and collinear corrections
- multiscale processes: logs of the ratio of very different scales

Huge radiative corrections (QCD)
Moreover, multiparticle final states are the signal for new physics

ME: why loops ?



Perturbative view: higher orders improve systematically the precision of the theoretical predictions (estimated by varying the renormalization/factorization scales) for background and signal

LO: fails to describe normalization (up to a factor 2). Monte Carlo event generators (LO + parton showers) : improves the shape of distributions, but normalization still underestimated

NLO: first reliable estimate of central value

NNLO: first serious estimate of the theoretical error

One-loop amplitudes

The classical paradigm for the calculation of one-loop diagrams was established in **1979**

Calculation of one-loop scalar integrals

Reduction of tensor one-loop integrals to scalar integrals

Not adequate for processes beyond 2→2 (Gramm determinants+large number of Feynman diagrams)

Nuclear Physics B
Volume 153, 1979, Pages 365-401

Scalar one-loop integrals

G. 't Hooft, M. Veltman

Received 16 January 1979

Nuclear Physics B
Volume 160, 26 Nov 1979, Pages 151-207

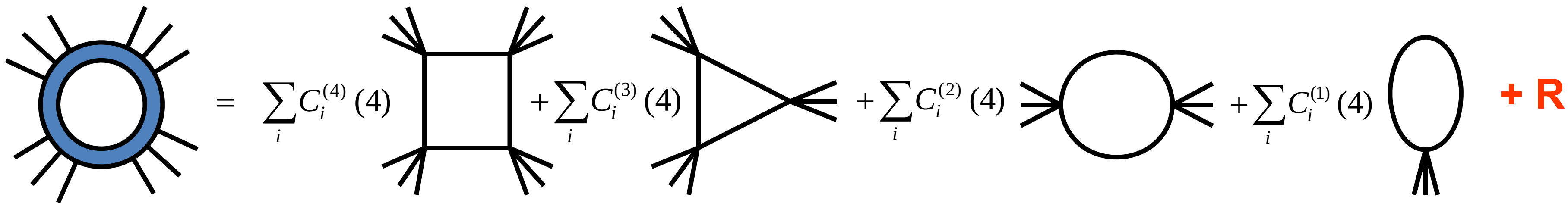
One-loop corrections for e+e− annihilation into μ+μ− in the Weinberg model

G. Passarino, M. Veltman

Received 22 March 1979

Generalized Unitarity: the one-loop basis

A dimensionally regulated n-point one-loop integral (scattering amplitude) is a linear combination of scalar boxes, triangles, bubbles and tadpoles with rational coefficients (Feynman Tree Theorem)



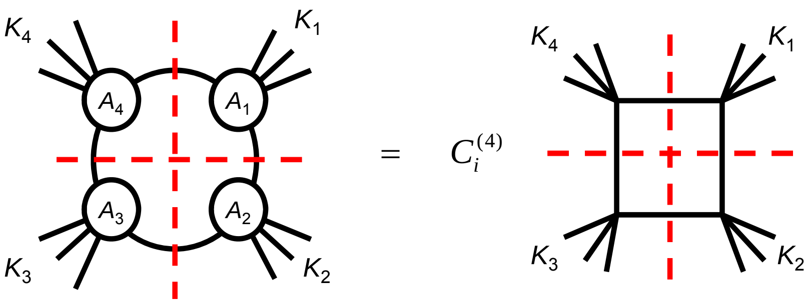
- The task is reduced to determining the coefficients: by applying **multiple cuts** at both sides of the equation [Brito, Cachazo, Feng]

- Pentagons and higher n-point functions can be reduced to lower point integrals and higher dimensional polygons that only contribute at O(ε) [Bern, Dixon, Kosower]

- R is a finite piece that is entirely rational: can not be detected by four-dimensional cuts

Generalized Unitarity

Quadruple cut



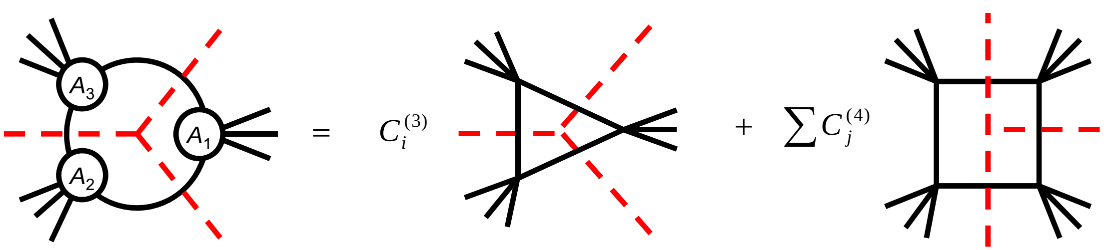
The discontinuity across the leading singularity is unique

$$C_i^{(4)} = A_1 \times A_2 \times A_3 \times A_4$$

Four on-shell constrains
➡ freeze the loop momenta

A_i **tree level** scattering amplitudes

Triple cut



Only three on-shell constrains ➡ one free component of the loop momentum

And so on for **double and single cuts**

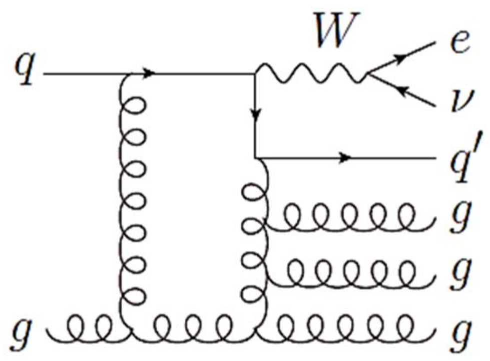
- **OPP** [Ossola, Pittau, Papadopoulos]: a systematic way to extract the coefficients

Rational terms

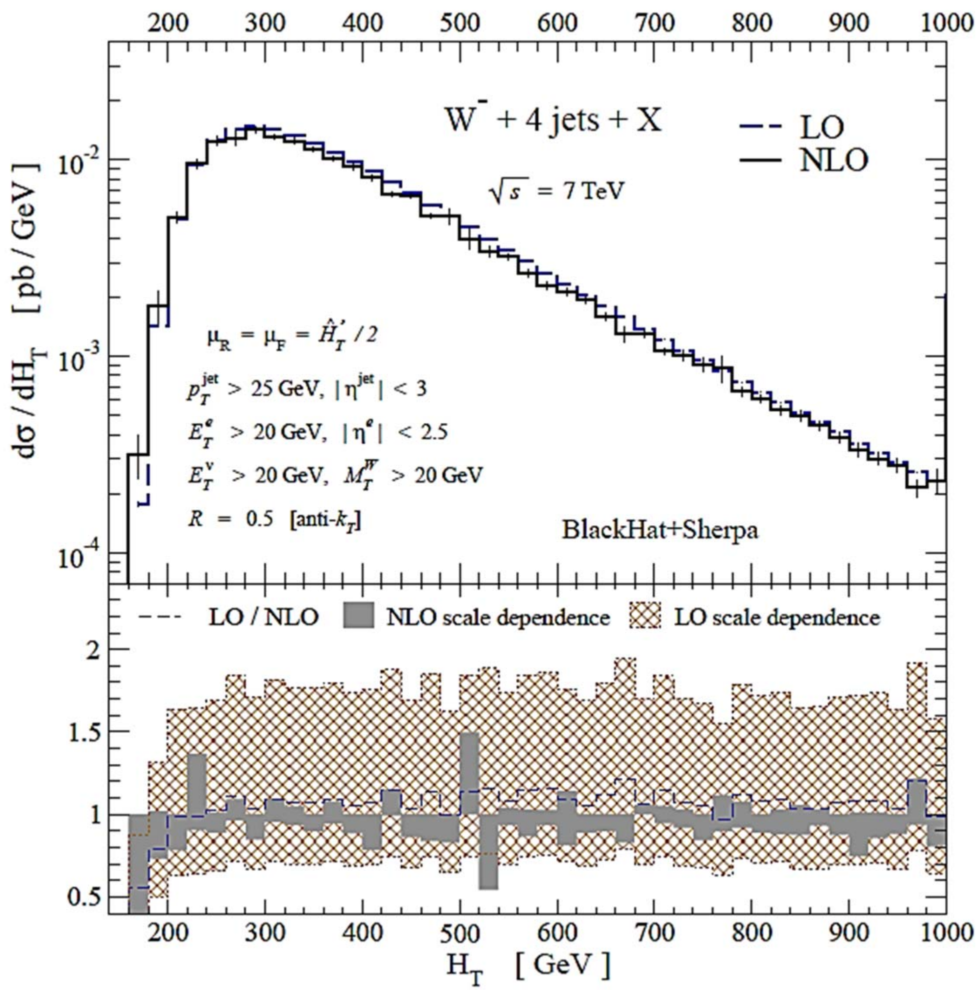
d-dimensional cuts, recursion relations (BCFW), Feynman rules …

W+4 jets at NLO

Sample diagram

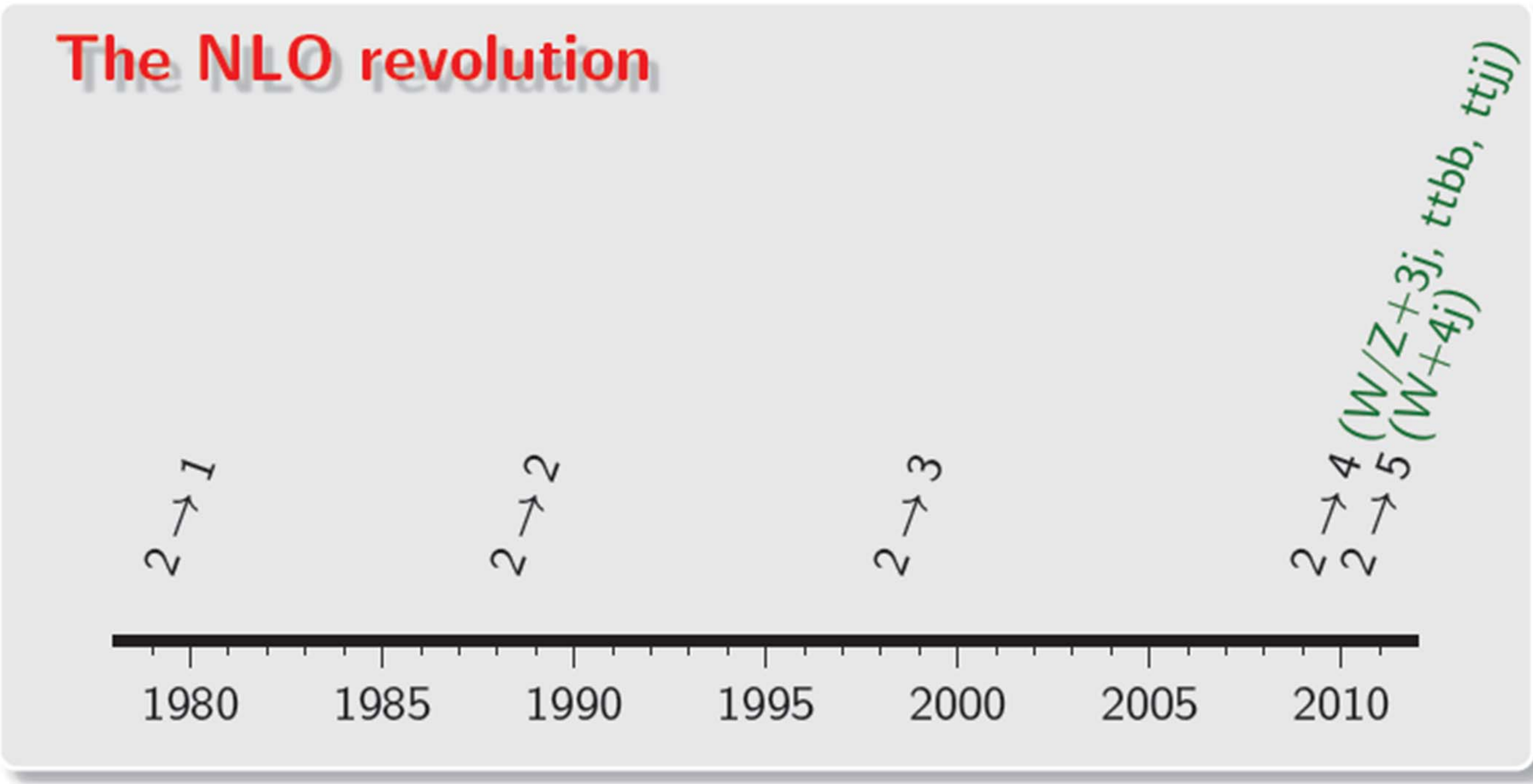


[Berger et al., 10]



- First pp → 5 (up to heptagons) Leading color calculation (3% accurate for lower multiplicities)
- Dominant background to top quark production
- Significant reduction of theoretical uncertainties
- Z+4jets (background to SUSY), 2011

[G. Salam, ICHEP 2010]

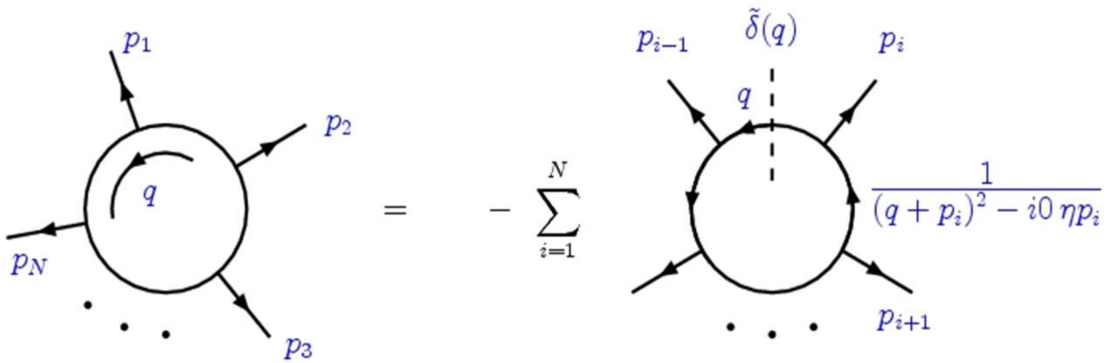


2→4 processes also from Feynman methods
[NB: only few years ago this was considered impossible]

Beyond one-loop: duality

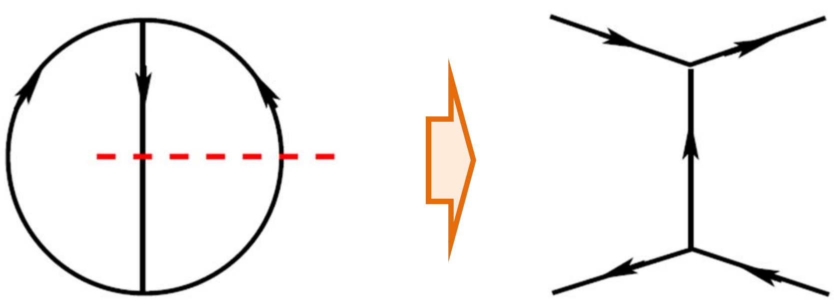
[Catani, Gleisberg, Krauss, GR, Winter, 08]

duality relation between one-loop integrals (one-loop scattering amplitudes) with an arbitrary number of external legs (momenta) and corresponding **single-cut** bremsstrahlung integrals.



- The duality relation is realised by modifying the customary "+i0" prescription of the Feynman propagators;

duality relation at higher orders
open any two-loop (three-loop) diagram to a **tree-level diagram** with the minimal number of cuts (= number of loops)

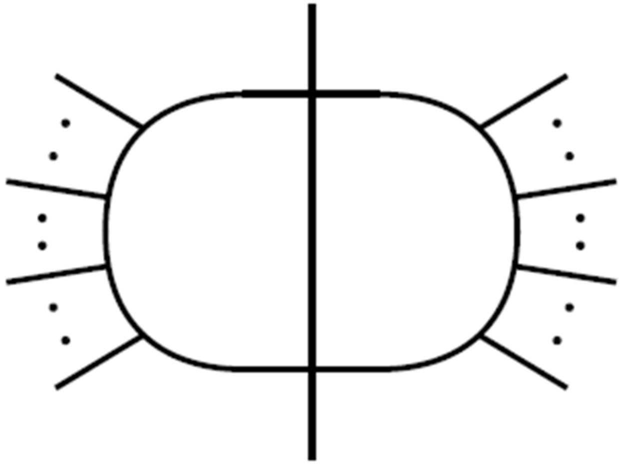


[Draggiotis talk]

[Bierenbaum, Catani, Draggiotis, GR, 10]
[See also Caron-Huot]

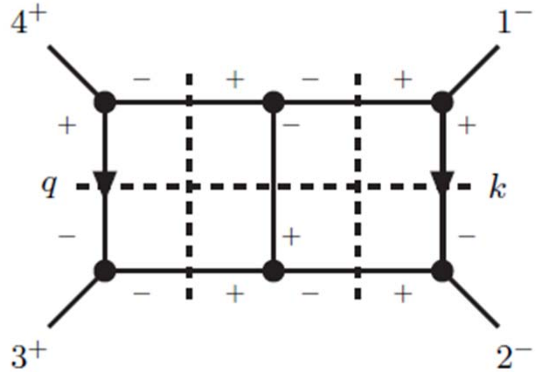
Beyond one-loop: Unitarity

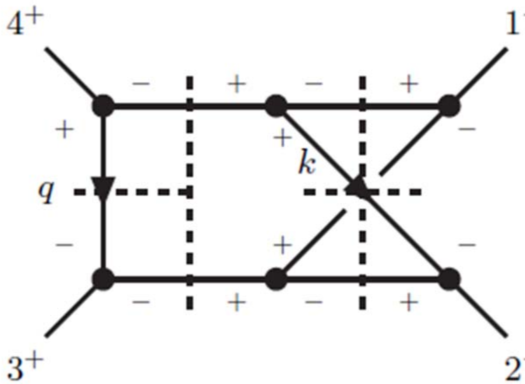
Towards a Basis for Planar Two-Loop Integrals
Gluza, Kajda, Kosower
arXiv:1009.0472



Integrand-Reduction at two-Loops
Mastrolia, Ossola
arXiv:1107.6041

Planar and non-planar simplest diagramas without any apriori knowledge of the integral basis





Theoretical Tools

Higher multiplicities

Parton Shower (PS): Pythia, Herwig, Ariadne
LO Monte Carlo event generators (+ PS usually): Alpgen, Helac, Madgraph, Sherpa

NLO partonic

- **Analytic:** MCFM
- **Feynmanists:** [Denner,Dittmaier], VBFNLO, Golem, FeynCalc
- **Unistarists:** Blackhat/Sherpa, Helac-NLO/Cuttools, Rocket, Samurai, MadLoop

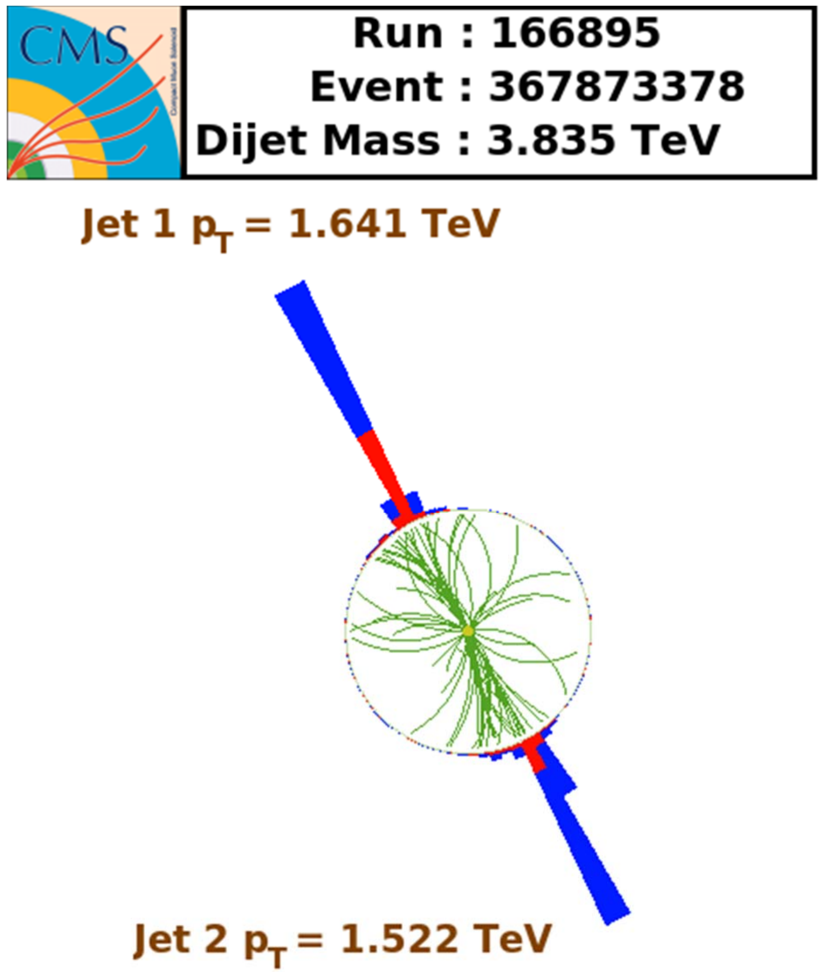
NLO + PS: aMC@NLO, POWHEG, MC@NLO

NLO + NLL (NNLL) analytic resummations: CAESAR, ResBos

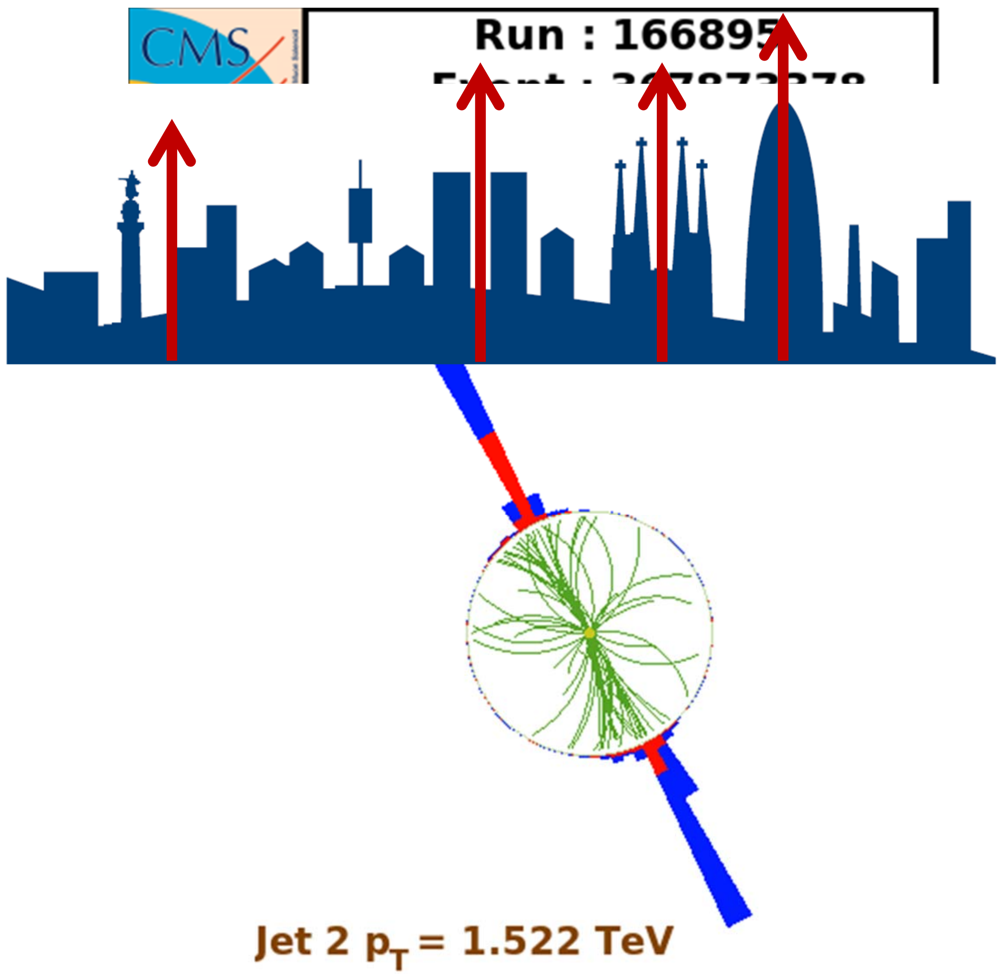
NNLO approx.: Hathor
NNLO inclusive: gg→H, VBF@NNLO
NNLO exclusive with flexible cuts: FEHIP, H@NNLO, FEWZ, DY@NNLO
NNLO + NNLL analytic resummations

Lower multiplicities
Higher precision

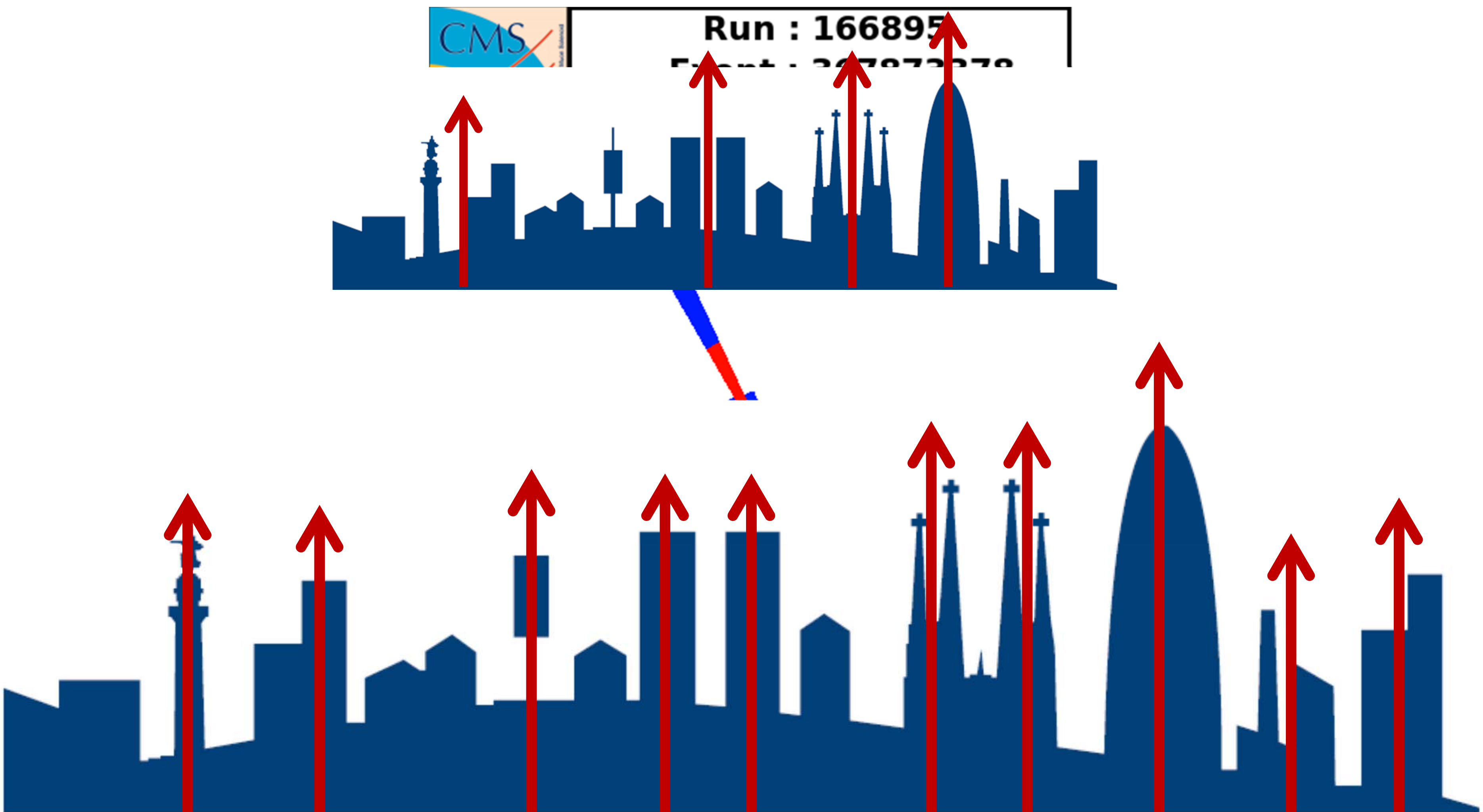
jetography


CMS
Run : 166895
Event : 367873378
Dijet Mass : 3.835 TeV
Jet 1 p_T = 1.641 TeV
Jet 2 p_T = 1.522 TeV

jetography



jetography



The anti-k_T jet algorithm

[Cacciari, Salam, Soyez 08]

- Jet algorithms were of common use at **LEP**, e.g. $d_{ij} = 2\frac{\min(E_i^2, E_j^2)}{s}(1-\cos\theta_{ij})$
- But **Tevatron** uses mostly **cones** to define jets (not IR safe)
- **ATLAS and CMS** adopted **anti-k_T** as default

anti-k_T

$$d_{ij} = \frac{1}{\max(k_{Ti}^2, k_{Tj}^2)}\frac{\Delta R_{ij}}{R^2} \qquad d_{iB} = \frac{1}{k_{Ti}^2} \qquad \Delta R_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Compute the smallest distance d_{ij} or d_{iB},
and either cluster i and j together or identify i as a jet

- Clusters hardest particles first
- IR safe, and cone-shaped jets
- Easier to get jet energy scale right

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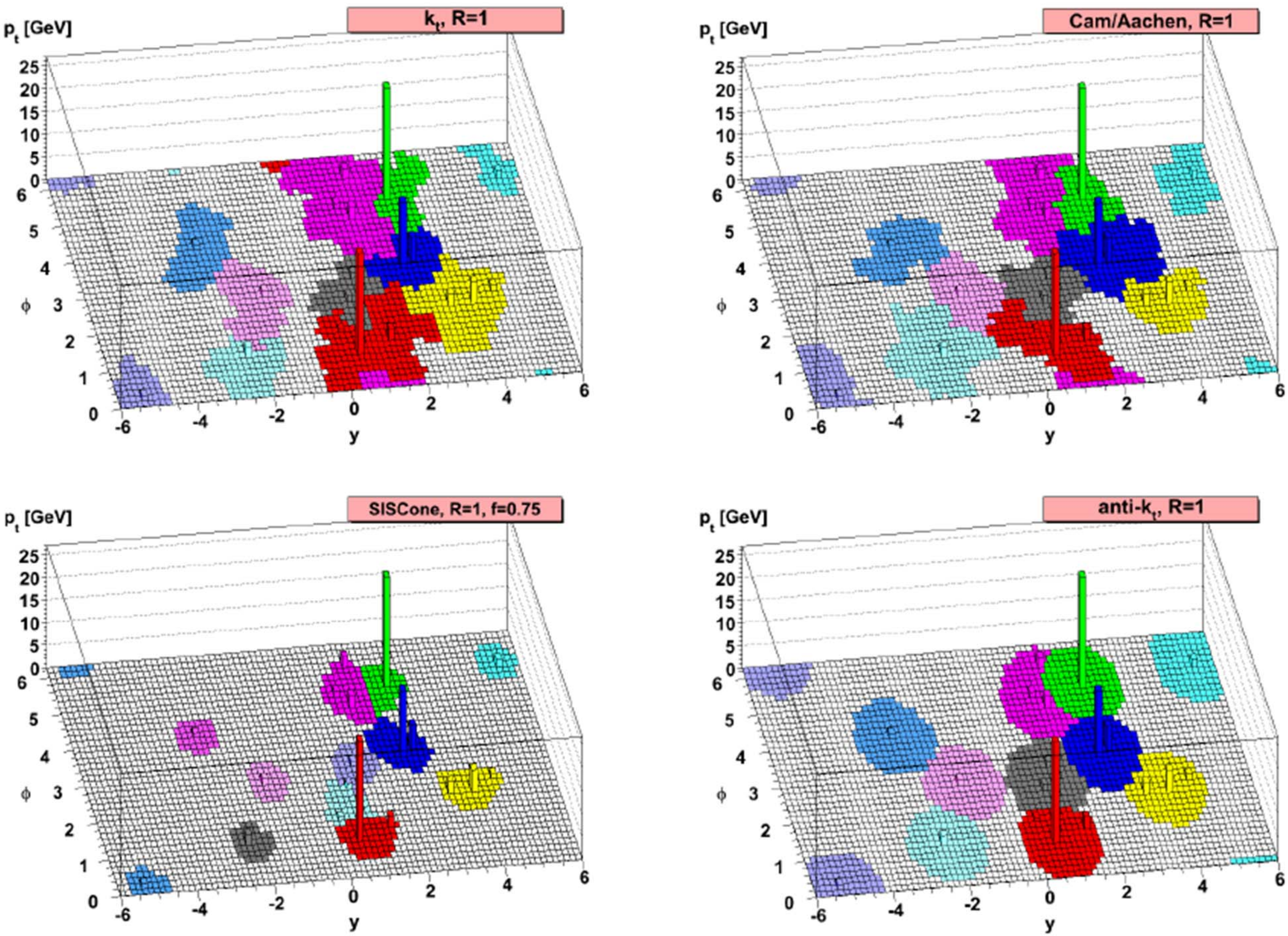
For the first time ever, a hadron collider will carry out measurements that can be consistently compared with theoretical (perturbartive QCD) calculations

[Cacciari, Salam, Soyez 08]



Jet substructure

[Almeida, Butterworth, Cacciari, Chen, Davison, Ellis, Falkowsky, Han, Katz, Kim, Kribs, Krohn, Lee, Martin, Nojiri, Perez, Plehn, Racklev, Rehermann, Roy, Rojo, Rubin, Salam, Shelton, Sreethawong, Son, Soyez, Sung, Thaler, Tweedie, Schwartz, Seymour, Soper, Spannowski, Sterman, Virzi, Vos, Wang, Zhu, …]

The LHC is the first place where heavy particles (~ 100 GeV) are produced copiously well **above threshold**

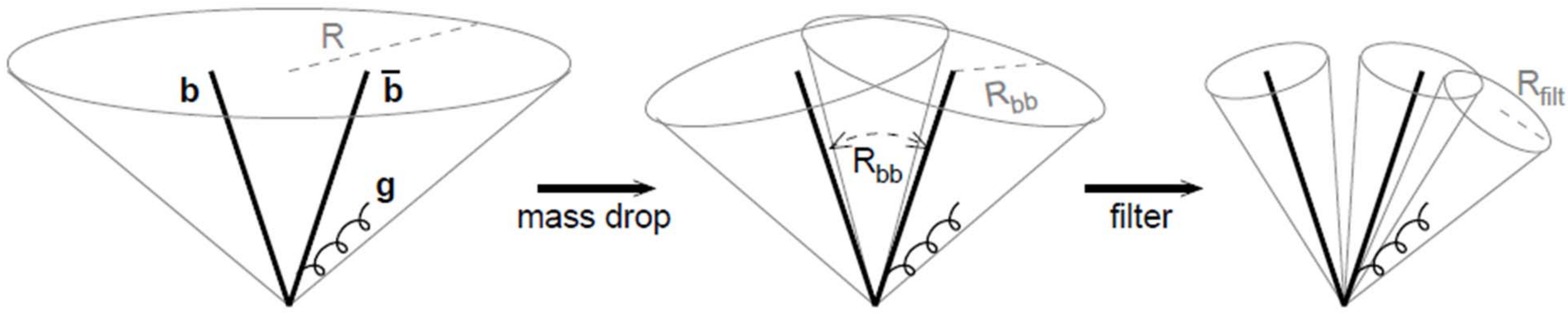
They are often very **boosted**, and decay hadronically

Decay products appear as a **single jet**

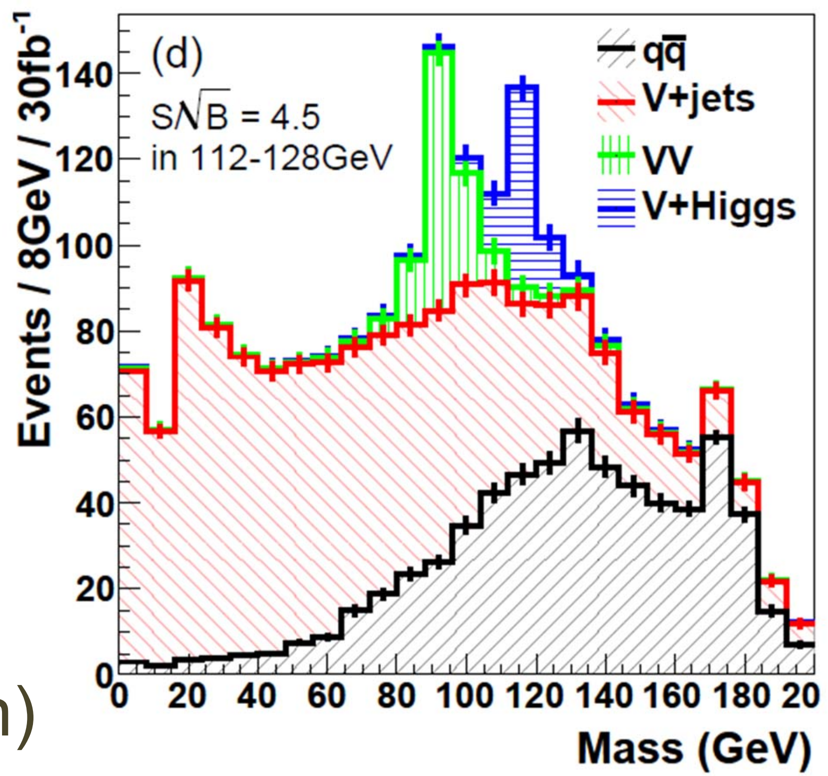
Need to examine the jet substructure to get the physics out

e.g. *ZH*, *WH* with *H*→ $b\bar{b}$

[Butterworth, Davison, Rubin, Salam 08]



- High p_T Higgs boson decaying to $b\bar{b}$: **back-to-back** to the Z/W
- Lower rates compensated by reduced backgrounds
- Recovers ZH and WH as significant channels for a **light Higgs discovery** (and couplings determination)



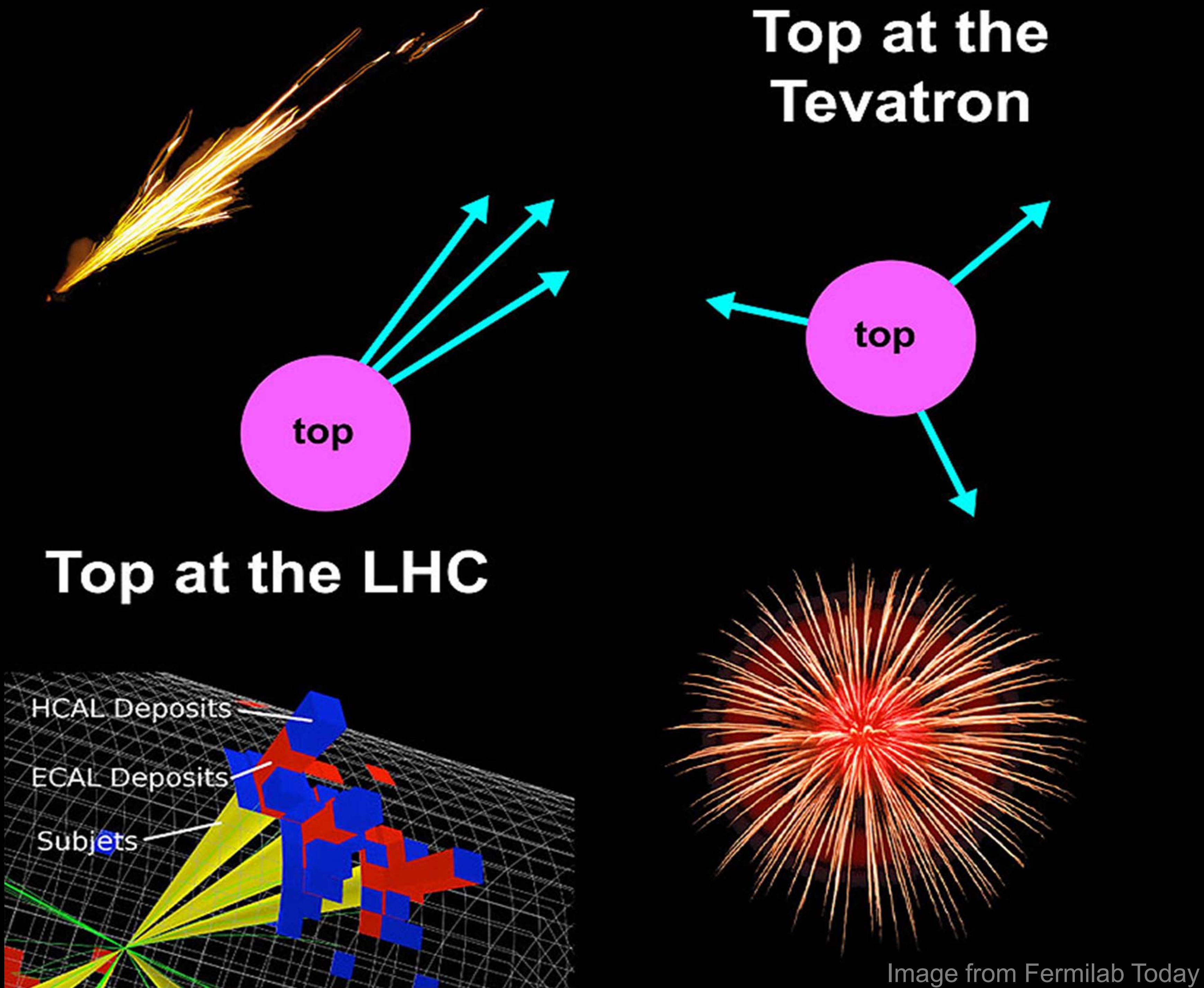


Image from Fermilab Today

Top at the

The top quark is the heaviest known elementary particle:
it plays a fundamental role in many extensions of the Standard Model (SM) / alternative mechanisms of EWSB.

Huge statistics from top-antitop quark pair production

Tevatron: σ = 7.6 (5) pb

Integrated luminosity of 10 fb^{-1}: 7×10^4 top quark pairs

LHC @7 TeV: σ = 160 (10) pb

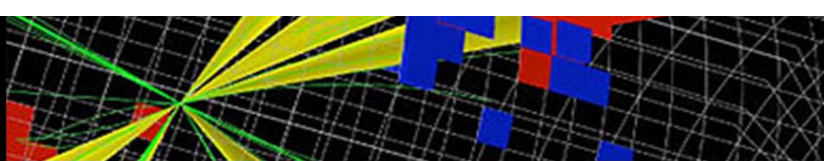
5 fb^{-1} (20-100 fb^{-1} by the end of 2012 ?): 5×10^5 ($2\text{-}10 \times 10^6$) top quark pairs

LHC @14 TeV: σ = 940 (80) pb

with 10 fb^{-1}/year: millions of top pairs per year

⇓

Production and decay channels are promising probes of new physics.



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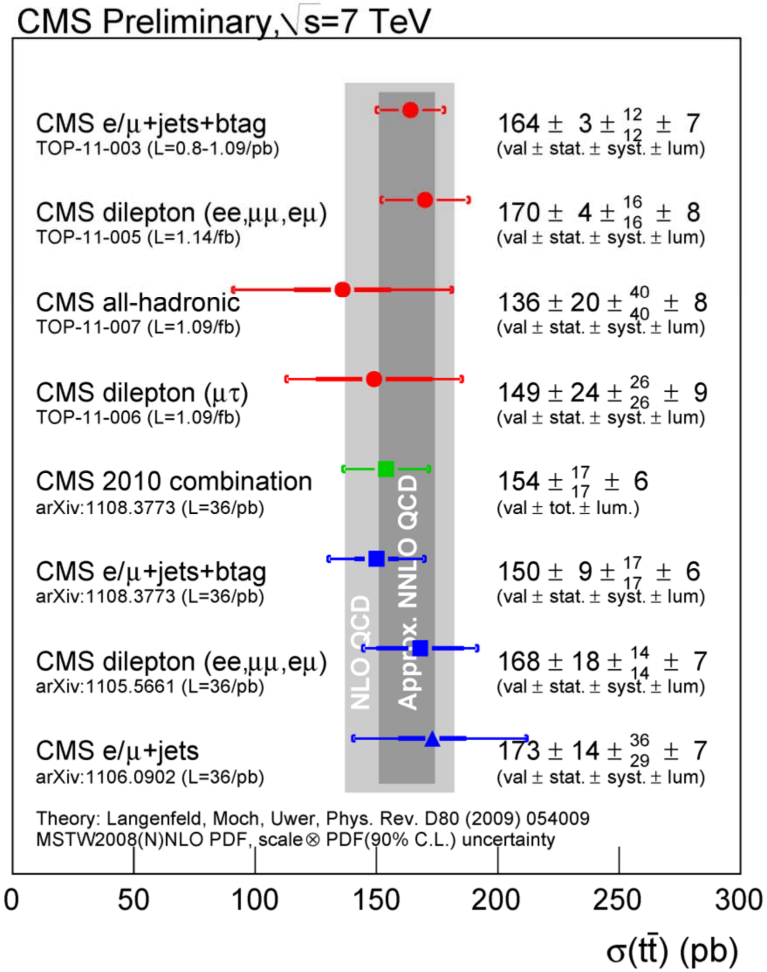
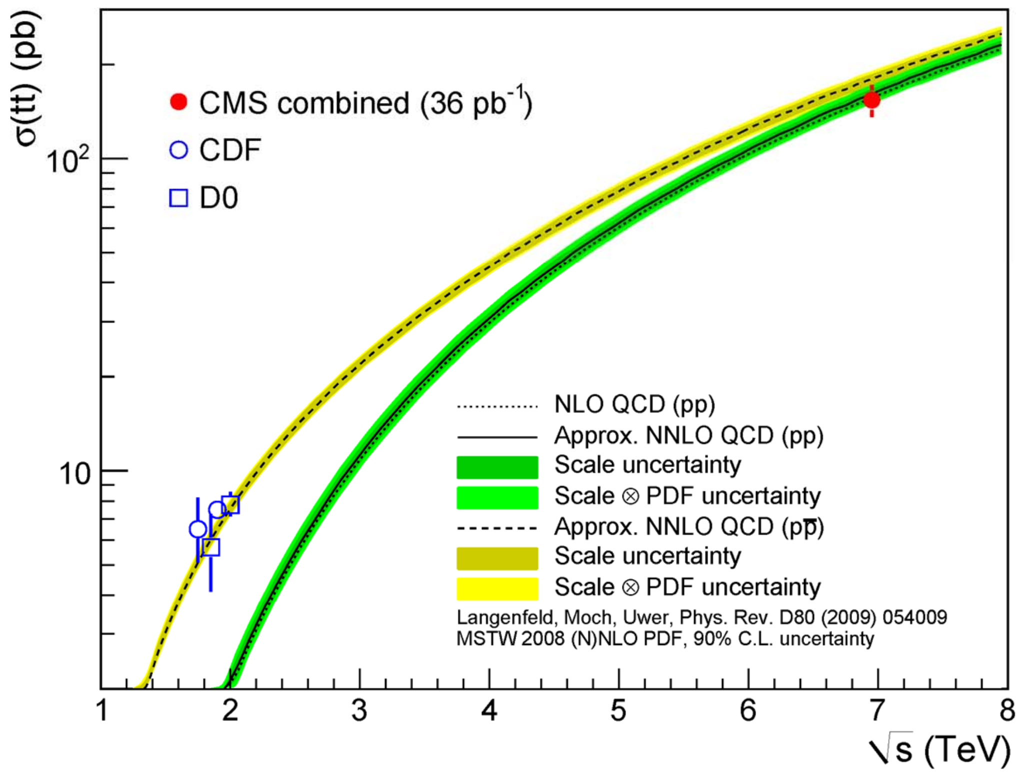




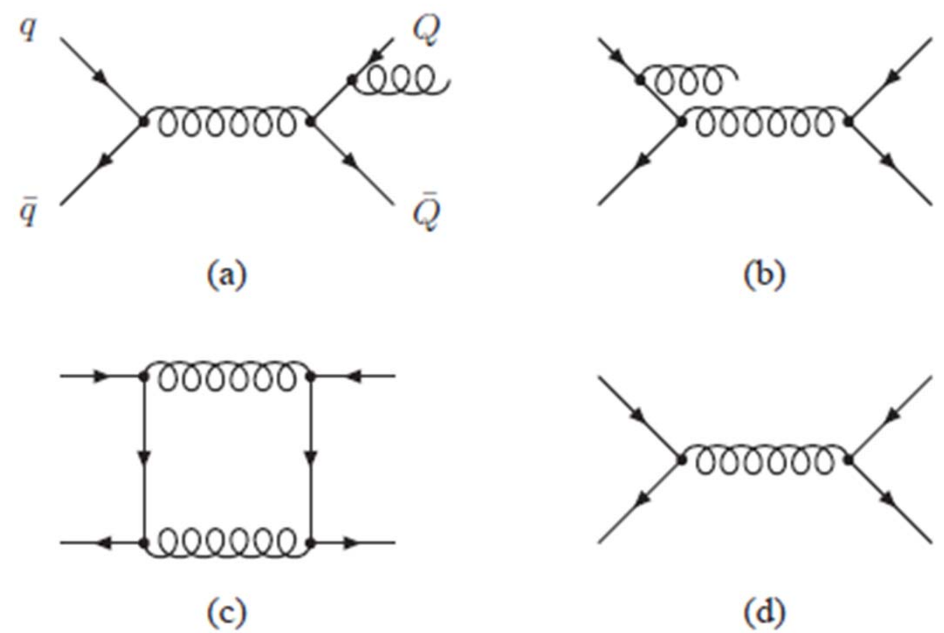
- Total cross-section in good agreement with **NLO QCD** (approx. NNLO)

- Full NNLO on-going [Bonciani, Ferroglia, Anastasiou, Czacon …]

Inclusive charge asymmetry at Tevatron

Since 2008, a systematic 1-2σ **positive** discrepancy with the SM

[Kühn, GR,1998; arXiv:1109.6830]



Charge conjugation symmetry* $(N_{\bar{t}}(y) = -N_t(-y))$

forward-backward

$$A_{\mathrm{lab}} = \frac{N(y_t>0)-N(y_{\bar{t}}>0)}{N(y_t>0)+N(y_{\bar{t}}>0)} = \mathbf{0.056(7)}$$

$$A_{t\bar{t}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)} = \mathbf{0.087(10)} \quad \Delta y = y_t - y_{\bar{t}}$$

* CP violation arising from electric or chromoelectric dipole moments do not contribute to the asymmetry

- mixed QCD-EW interference included: factor 1.2 [Kühn, GR / Hollik, Pagani]
- stable to NLL threshold resummations (one per mille) [Almeida,Sterman,Vogelsang]
- NNLL threshold resummations [Ahrens,Ferroglia,Neubert,Pecjak,Yang]

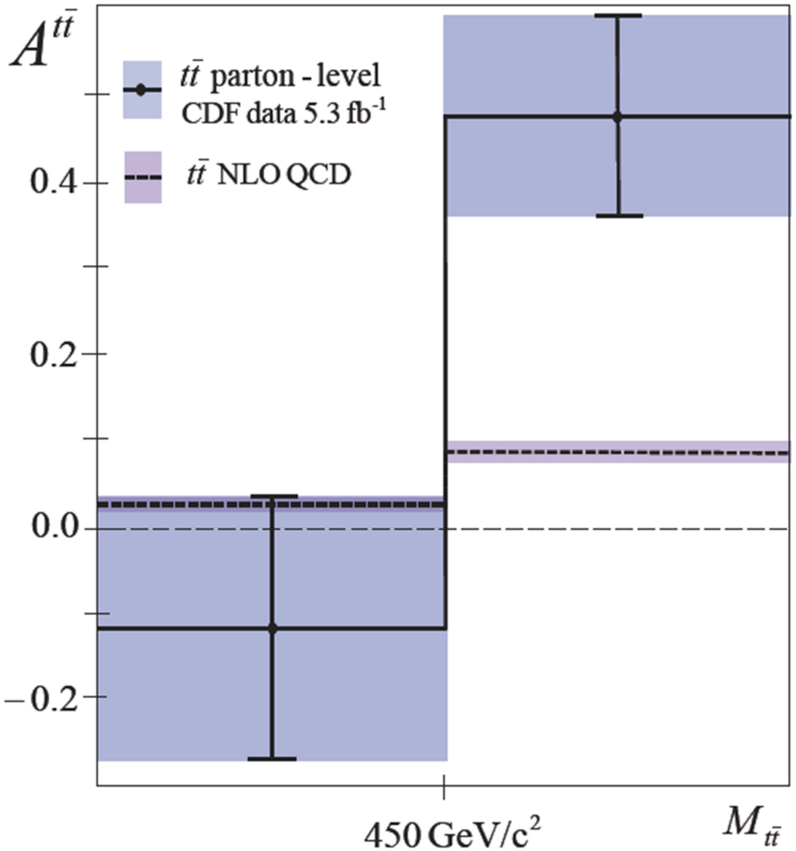
Not expanding the asymmetry in α_S : the asymmetry decreases by 20% at NLO (K factor), but only by 5% at NLO+NNLL

Invariant mass dependent charge asymmetry

CDF [PRD83 (2011)112003 arXiv:1101.0034] $t\bar{t}$ rest frame 5.3 fb^{-1}

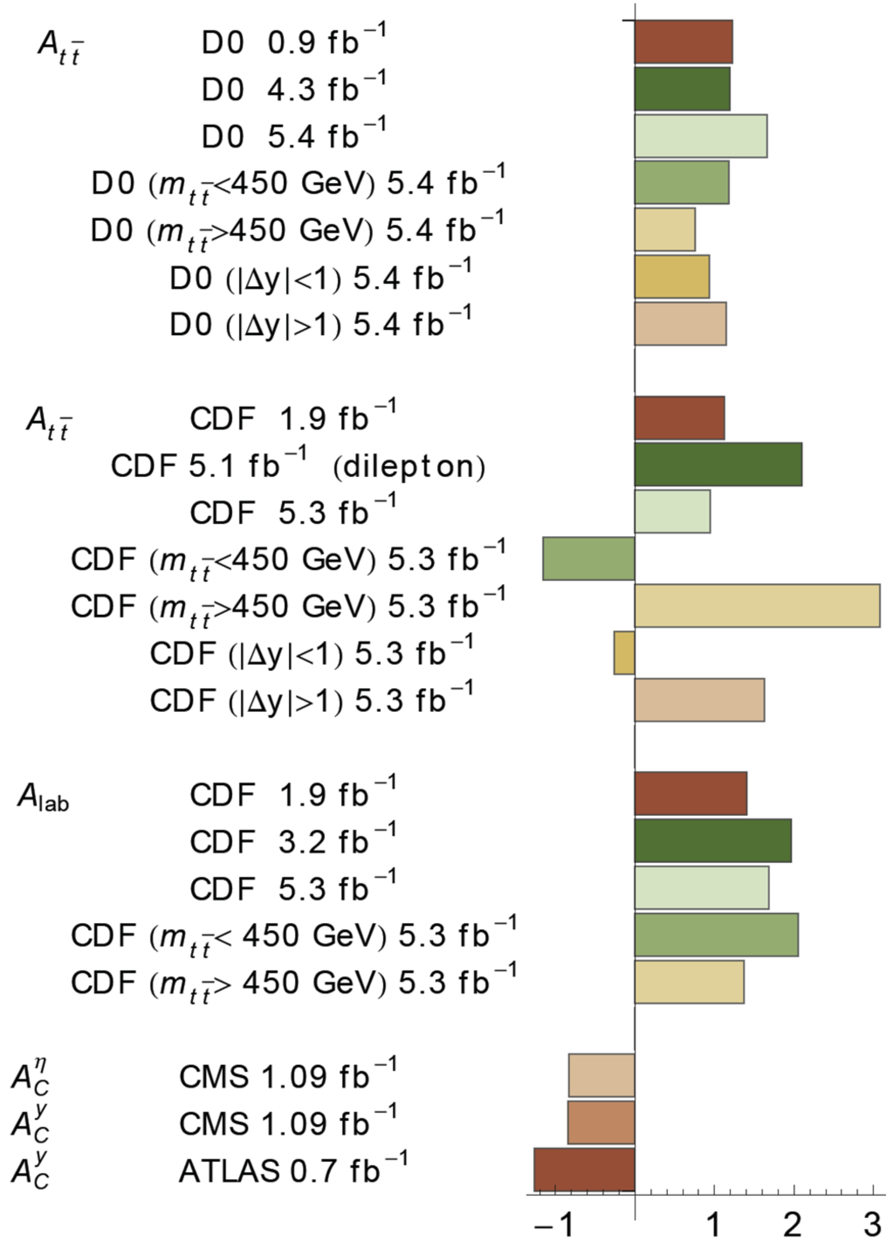
$$A_{t\bar{t}}(M_{t\bar{t}} < 450\ \text{GeV}) = -0.116 \pm 0.146\ (\text{stat}) \pm 0.047\ (\text{syst})$$

$$A_{t\bar{t}}(M_{t\bar{t}} > 450\ \text{GeV}) = 0.475 \pm 0.101\ (\text{stat}) \pm 0.049\ (\text{syst})$$



- below 450 GeV: negative asymmetry but still compatible with the SM within 1σ
- above 450 GeV: positive asymmetry, disagrees with the SM at 3.4σ
- The deviation from the SM in the lab frame is not as significant !!!

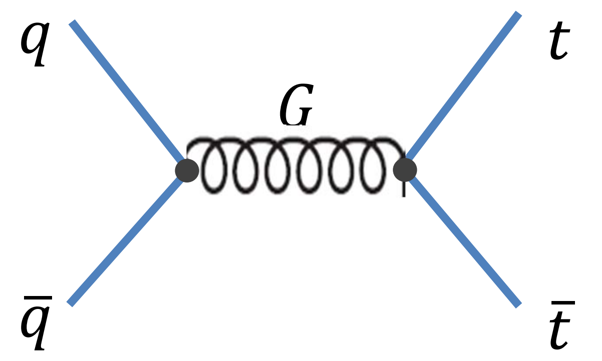
Tevatron (and LHC) summary



Axigluons $SU(3)_L$ x $SU(3)_R \rightarrow SU(3)_C$: s-channel

Color-octet resonances

$$\mathcal{L} = g_S T^a \bar{q}_i \gamma^\mu (g_V{}^{q_i} + g_A{}^{q_i} \gamma_5) G_\mu{}' q_i$$



might produce a charge asymmetry through the interference with the LO SM amplitude

But this asymmetry is negative because it is proportional to

$$(\hat{s} - m_G{}^2)\, g_A{}^q\, g_A{}^t$$

A positive asymmetry can be generated if

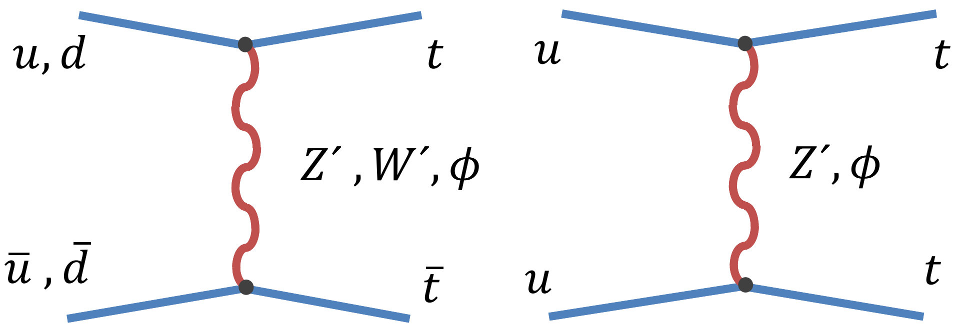
- very light axigluon: but would be visible in $M_{t\bar{t}}$: new decay channels to enlarge the width [Marques Tavares, Schmalz / Barcelo, Carmona, Masip, Santiago]

- vector-axial couplings of opposite sign: $\mathrm{sign}(g_A{}^q) = -\mathrm{sign}(g_A{}^t)$
[Ferrario, GR / Frampton,Shu,Wang / Bauer, Goertz, Haisch, Pfoh, Westhoff / Bai, Hewett, Kaplan, Rizzo / Zerwekh / Hewet, Shelton, Spannowsky, Tait, Takeuchi / Haisch, Westhoff / Aguilar-Saavedra, Perez-Victoria, …]

- squared of the BSM amplitude dominates, which is proportional to $g_V{}^q g_V{}^t g_A{}^q g_A{}^t$: large vector couplings [Ferrario, GR]

New physics in the t-channel

[Jung, Murayama, Pierce, Wells / Cheung, Keung,Yuan / Cao, Heng,Wu,Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria/ Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta]
Shu,Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung,Ko,Lee,Nam. Aguilar-Saavedra, Perez-Victoria / Patel, Sharma / Ligeti, Marques Tavares, Schmalz]



- Because of color algebra a Z' or W' in the s-channel do not interfere with the LO QCD amplitude
- Neither colored scalars

- A sizeable charge asymmetry requires **large flavour violating couplings** [Jung,Murayama,Pierce,Wells]
- **like sign $tt + \bar{t}\bar{t}$**, very constrained at Tevatron, and the LHC
- Relatively light Z´ and/or W´: O(200-700 GeV), or O(1TeV) colored scalars

Transverse momentum of the $t\bar{t}$ pair

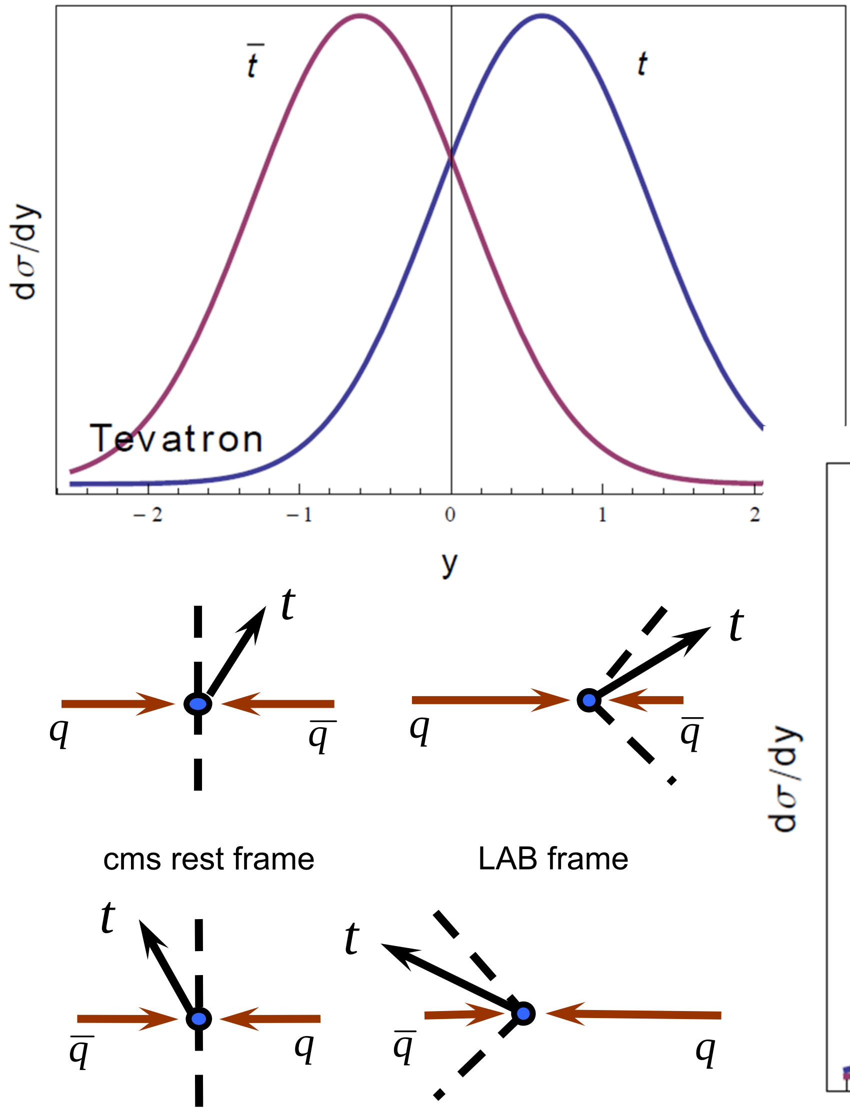
- the inclusive asymmetry is robust against higher order corrections [see also Melnikov]
- but diff. distributions might be quite sensitive ($t\bar{t}$+jet @NLO [Dittmaier, Uwer, Weinzierl / Alioli, Moch, Uwer])
- virtual + soft (positive) vs. real (negative)

$$A_{\rm lab} = 0.056(7) \qquad A_{t\bar{t}} = 0.087(10)$$

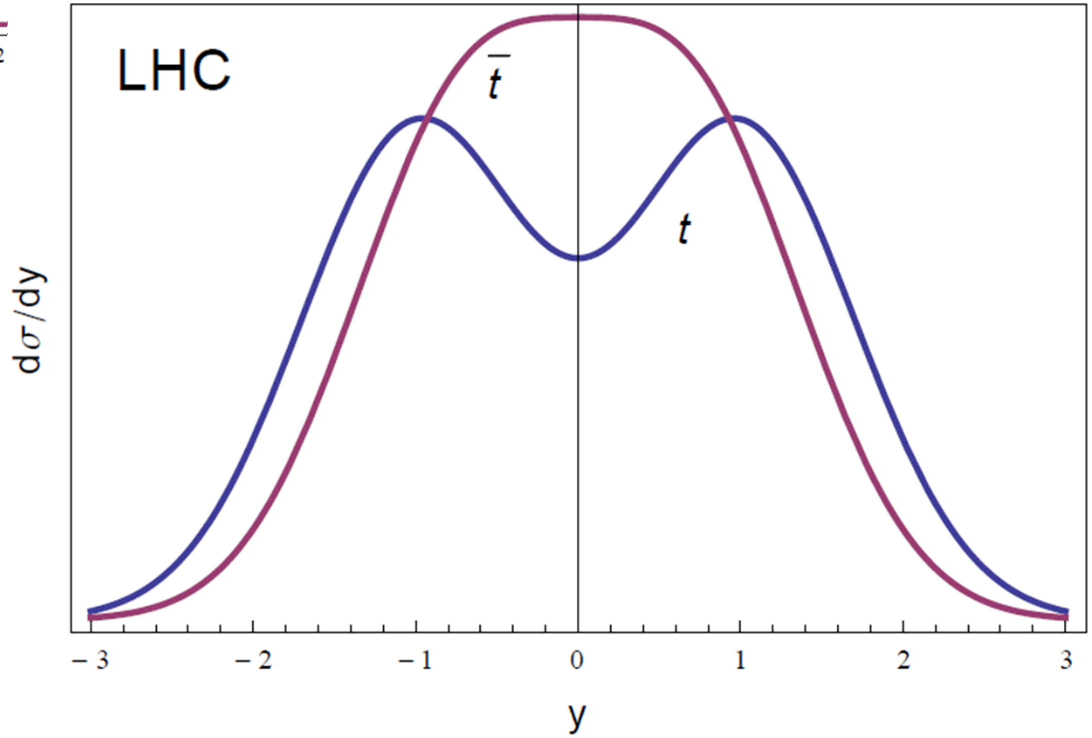
laboratory	$A_{\rm lab}$	$m_{t\bar{t}} < 450$ GeV	$m_{t\bar{t}} > 450$ GeV
$p_\perp^{tt} < 10$ GeV	0.090 (12)	0.047 (3)	0.161 (16)
$p_\perp^{tt} < 20$ GeV	0.076 (10)	0.040 (3)	0.137 (13)
$t\bar{t}$ rest frame	$A_{t\bar{t}}$	$m_{t\bar{t}} < 450$ GeV	$m_{t\bar{t}} > 450$ GeV
$p_\perp^{tt} < 10$ GeV	0.136 (16)	0.097 (8)	0.201 (19)
$p_\perp^{tt} < 20$ GeV	0.115 (13)	0.082 (7)	0.171 (16)

[Kühn, GR, arXiv:1109.6830]

From Tevatron to the LHC



LHC is symmetric ► no forward-backward but excess of tops (or antitops) in the forward and backward regions because incoming quarks carry more momenta than antiquarks



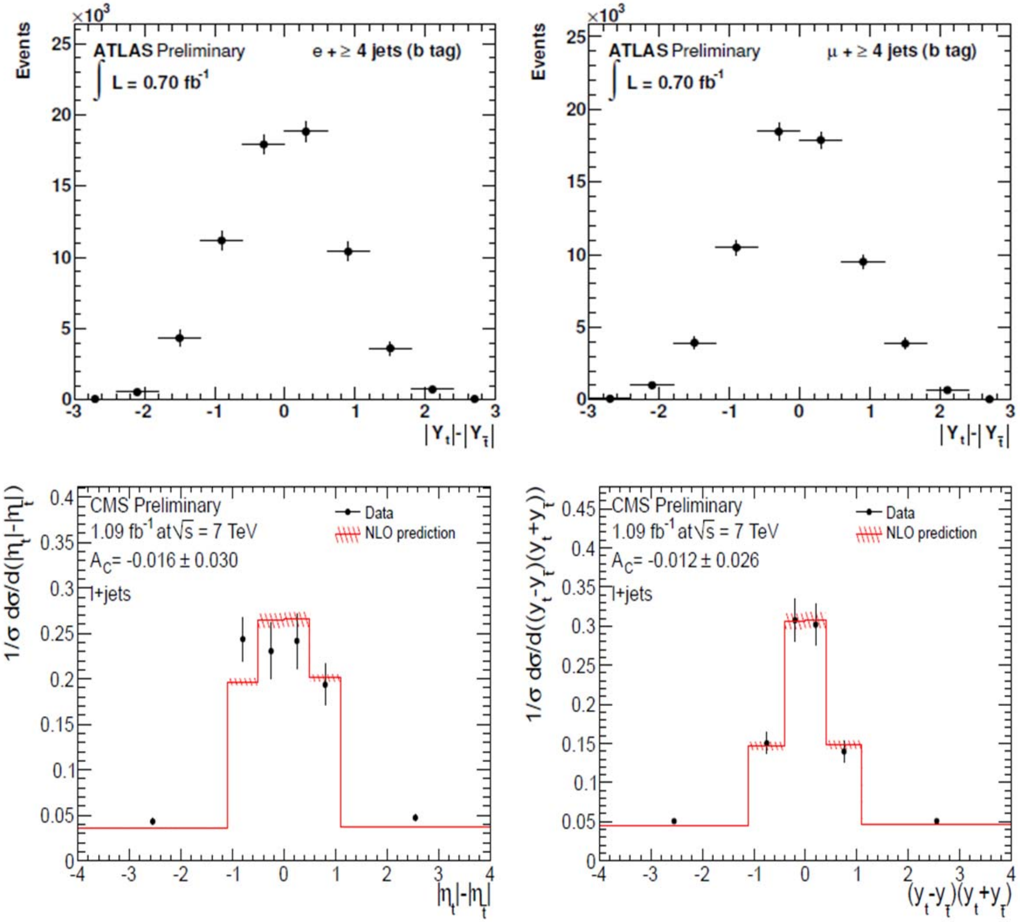
Cut-independent asymmetries

$$A_C^{\Delta} = \frac{N(\Delta>0) - N(\Delta<0)}{N(\Delta>0) + N(\Delta<0)}$$

$\Delta = |\eta_t| - |\eta_{\bar{t}}|, |y_t| - |y_{\bar{t}}|$ or $y_t^2 - y_{\bar{t}}^2$

$A_\eta^{SM} = 0.0136\ (8)$
$A_y^{SM} = 0.0115\ (6)$

[Kühn, GR, arXiv:1109.6830]



$A_C = -0.009 \pm 0.023\,(\text{stat.}) \pm 0.032\,(\text{syst.})$ (e+jets channel)

$A_C = -0.028 \pm 0.019\,(\text{stat.}) \pm 0.022\,(\text{syst.})$ (μ+jets channel)

$$A_C = -0.024 \pm 0.016\,(\text{stat}) \pm 0.023\,(\text{syst}),$$

$$A_C^{\eta} = -0.016 \pm 0.030\,(\text{stat.})^{+0.010}_{-0.019}(\text{syst.})$$

$$A_C^{y} = -0.013 \pm 0.026\,(\text{stat.})^{+0.026}_{-0.021}(\text{syst.})$$

- scaling the statistical error

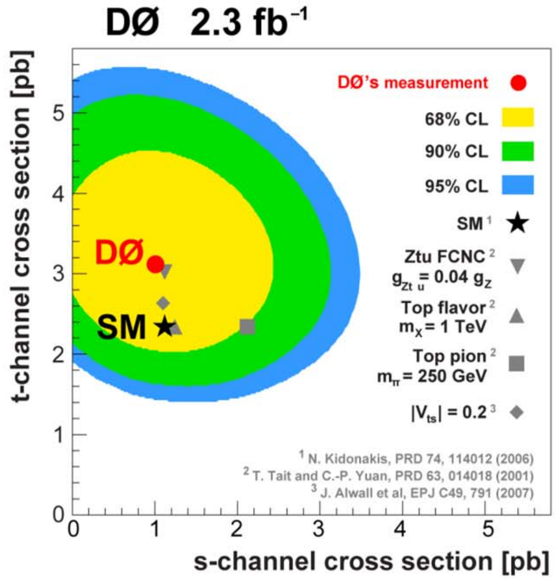
10 fb^{-1} : 8 per mille
100 fb^{-1} : 3 per mille

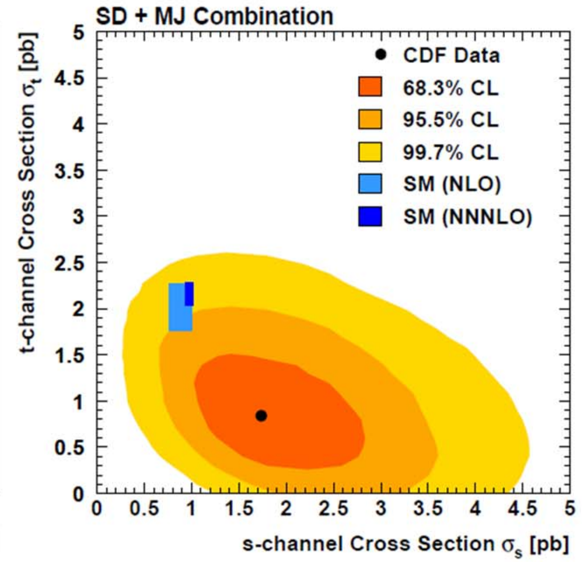
Other Tevatron anomalies

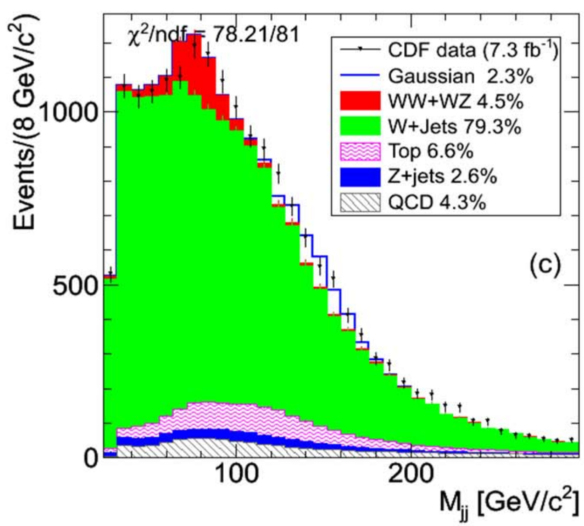
- s- versus t-channel cross-section in **single top** production (only CDF)
- 2σ excess in the tail of the H_T distribution = scalar sum of E_T (D0 and CDF) in top quark production
- 4.1σ excess in **W+2jets** dijet mass (CDF 1104.0699 and update to 7.3 fb^{-1}) not confirmed by D0 (1106.1921), ATLAS (CONF-2011-097)

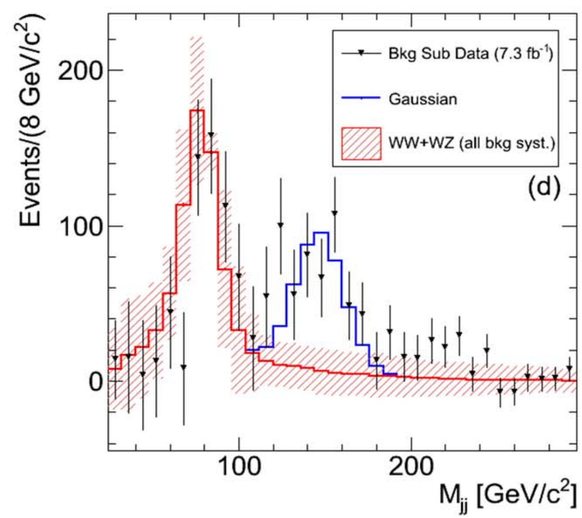
Related with excess in single top production [Sullivan, Menon]: *CDF uses MC to subtract single top background*

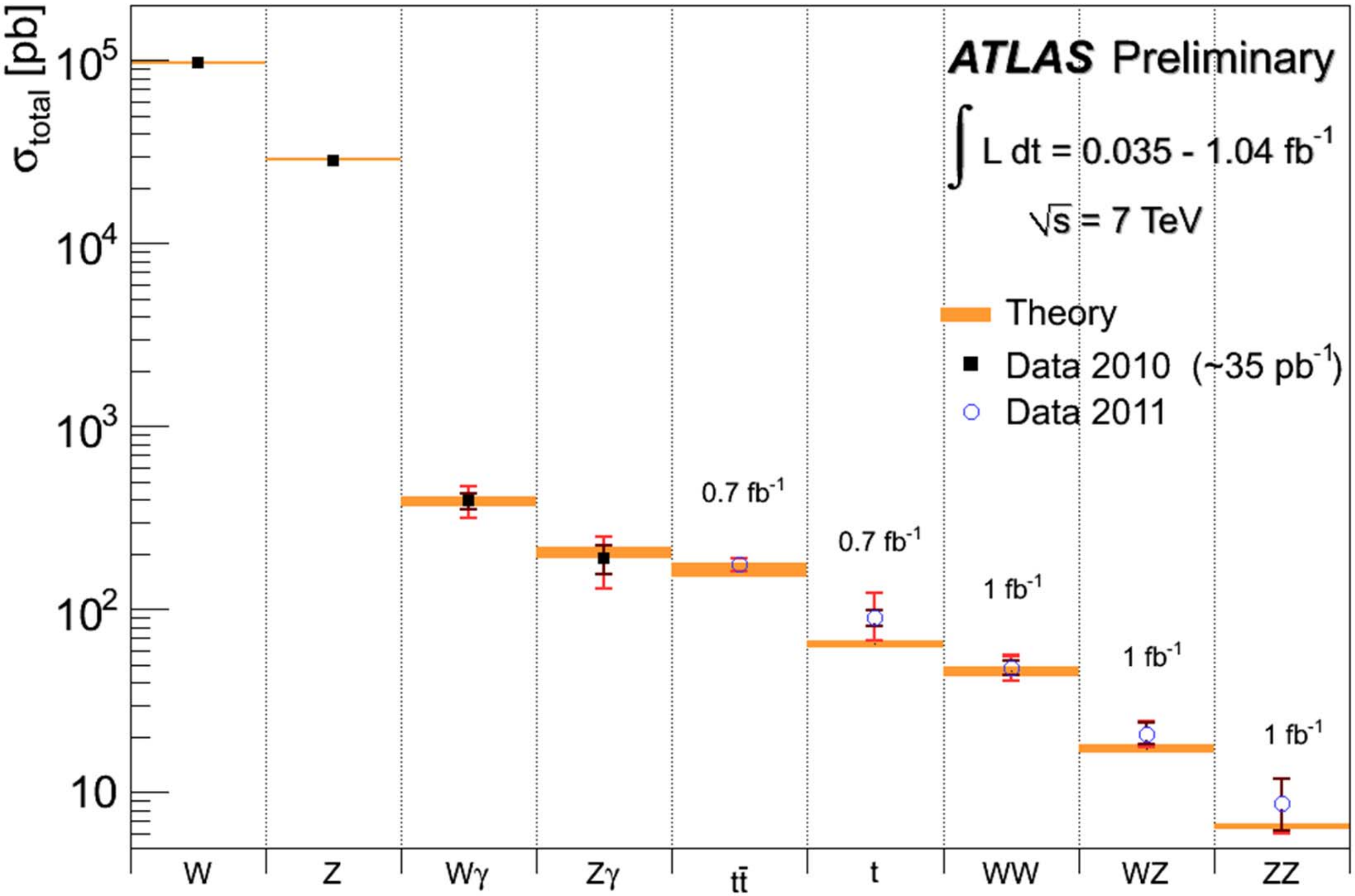
NLO *corrections* [aMC@NLO] *not responsible for the excess*







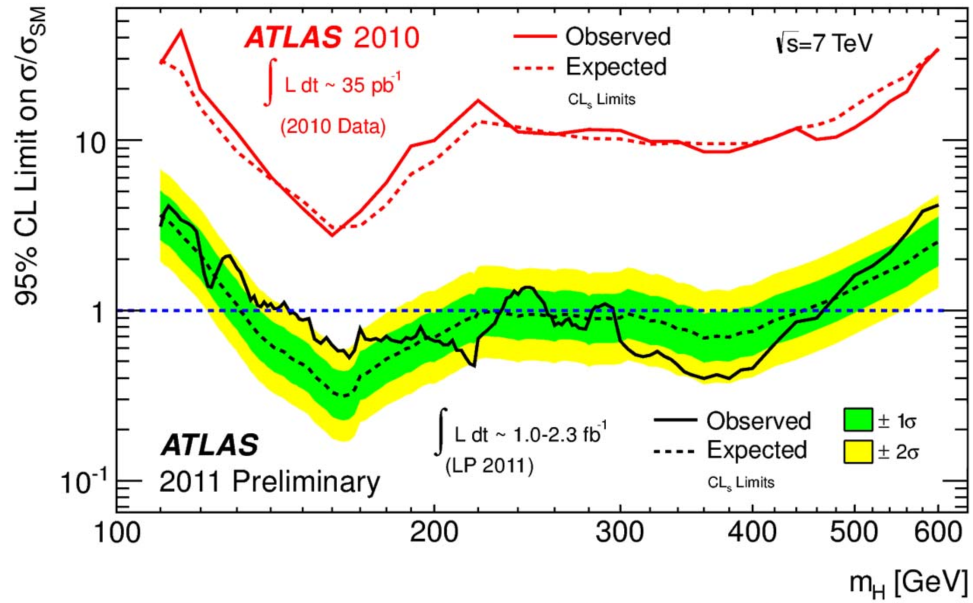


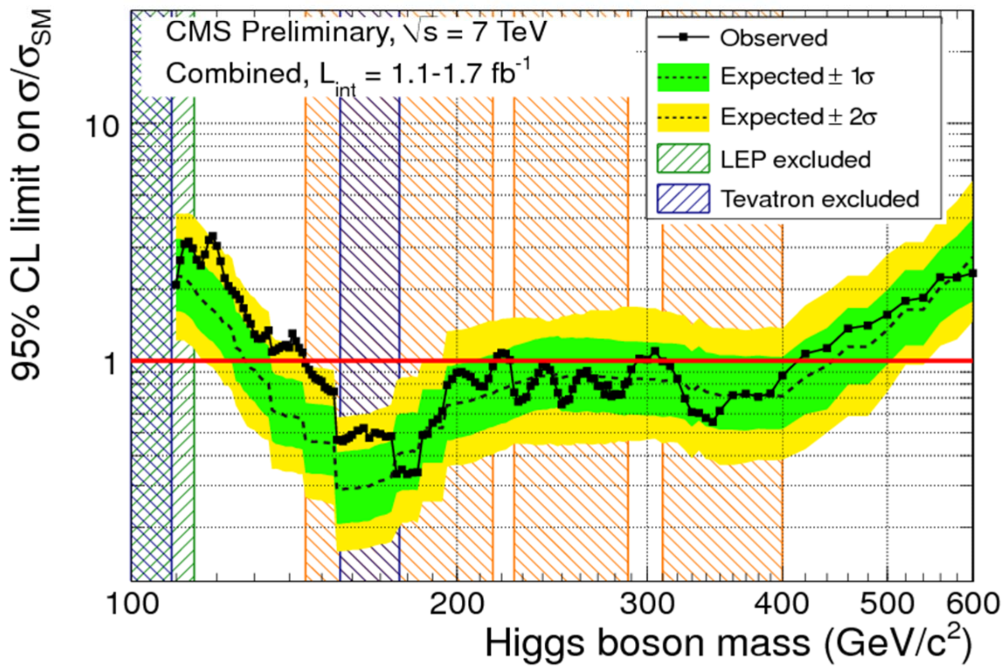


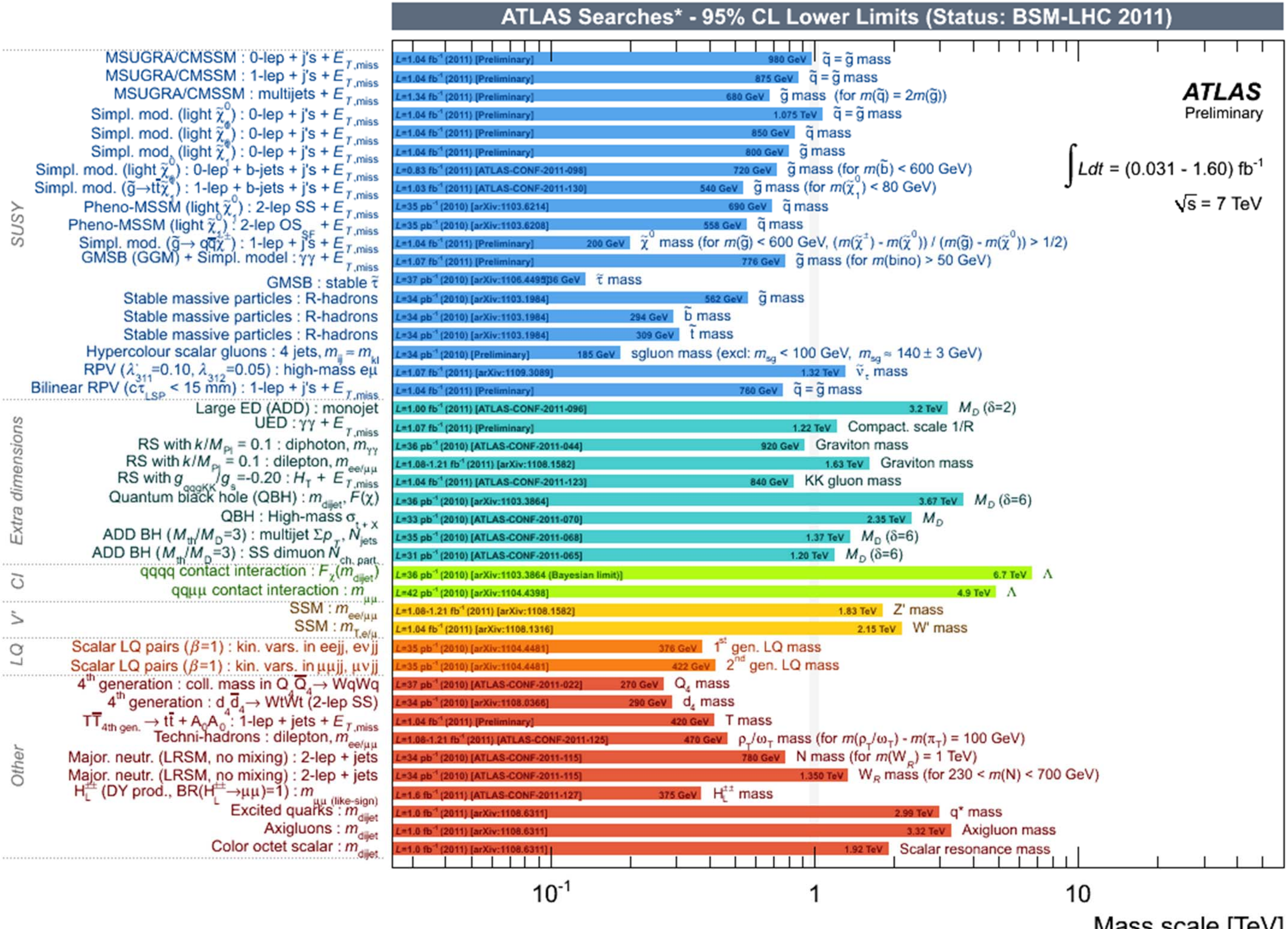
Good agreement with theory **(SM)**

Higgs boson

Higgs boson in the **most difficult** region







*Only a selection of the available results leading to mass limits shown

Conclusions

- Remarkable development of theoretical tools for the LHC in the last years
  - More choice of PDF´s
  - First tools for automated multiparticle NLO cross-sections
  - First NNLO calculations for precision observables
  - New standard jet algorithm at hadron colliders (anti-k_T), and jet substructure analysis
  - New developments in Parton Showers [López-Villarejo´s talk]

- Some anomalies from Tevatron, but in general a good agreement with the **SM**

- Strong bounds on new physics (**Λ_{BSM} > 1-3 TeV**), and **SM Higgs** constrained in the most difficult region