Improving the precision of high-energy simulation and analysis tools

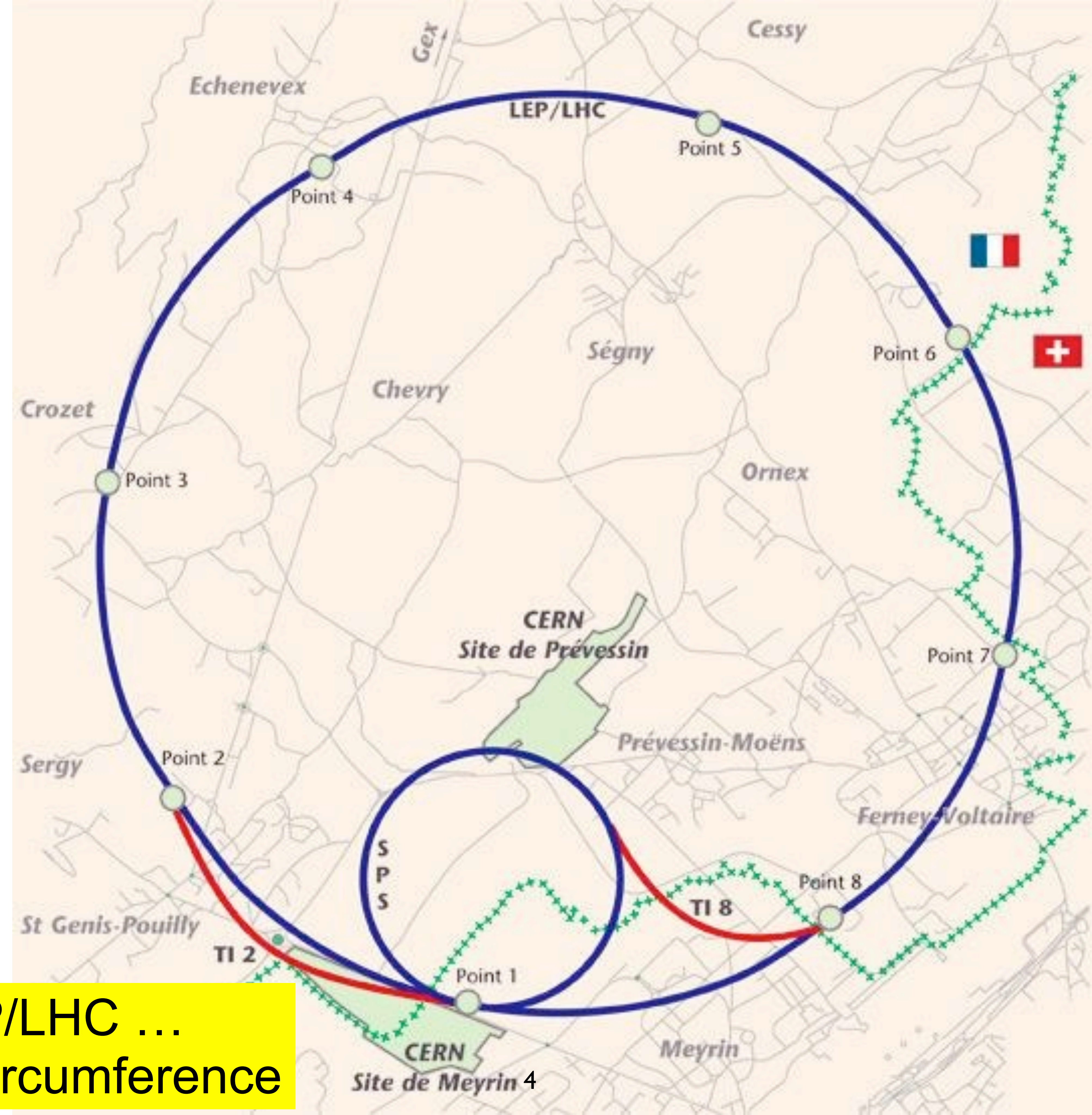
Bryan Webber
University of Cambridge

- Hadron Colliders
- Monte Carlo event generation
- Jet finding algorithms

Hadron Colliders

Large Hadron Collider

- Located at CERN near Geneva
- Proton-proton collisions at 8 TeV (currently)
- Main experiments ATLAS and CMS
- Design energy 14 TeV



LEP/LHC …
27 km circumference

LHC Beam - Stored Energy

- At high luminosity: 2808 bunches, 1.1 x 10^{11} protons/bunch, 7 TeV beams (design energy):

➡ **350 MJ stored energy per proton beam**

= Kinetic energy of 120 elephants each at 40 km/h

= Kinetic energy of fully loaded Airbus A320 at landing speed

= Kinetic energy of "Nimitz-class" US aircraft carrier at 4 mph

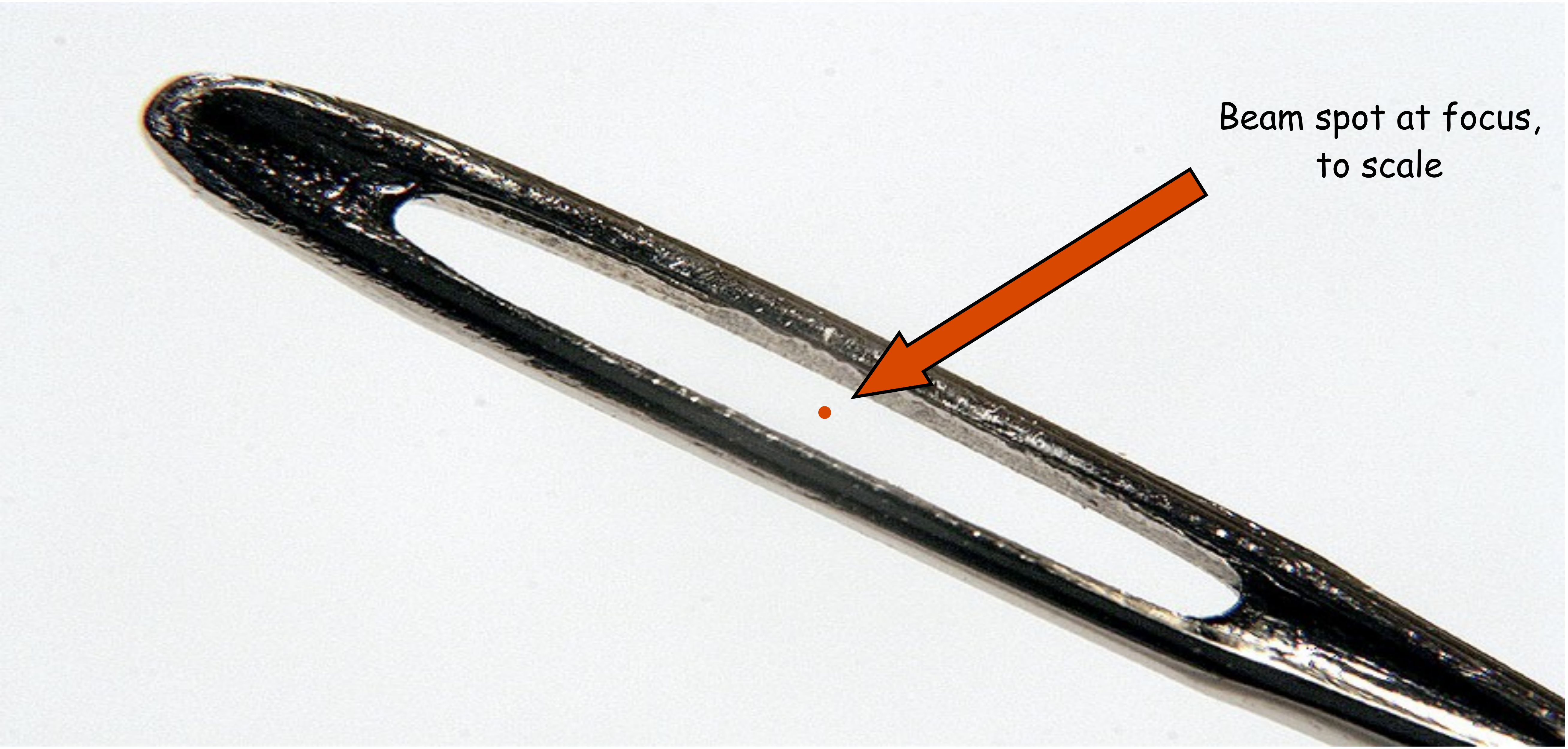
= Enough energy to melt 550 kg copper.

(+10 GJ stored in magnets)

➡ main problem at LHC is to control the stored energy and to avoid any damage

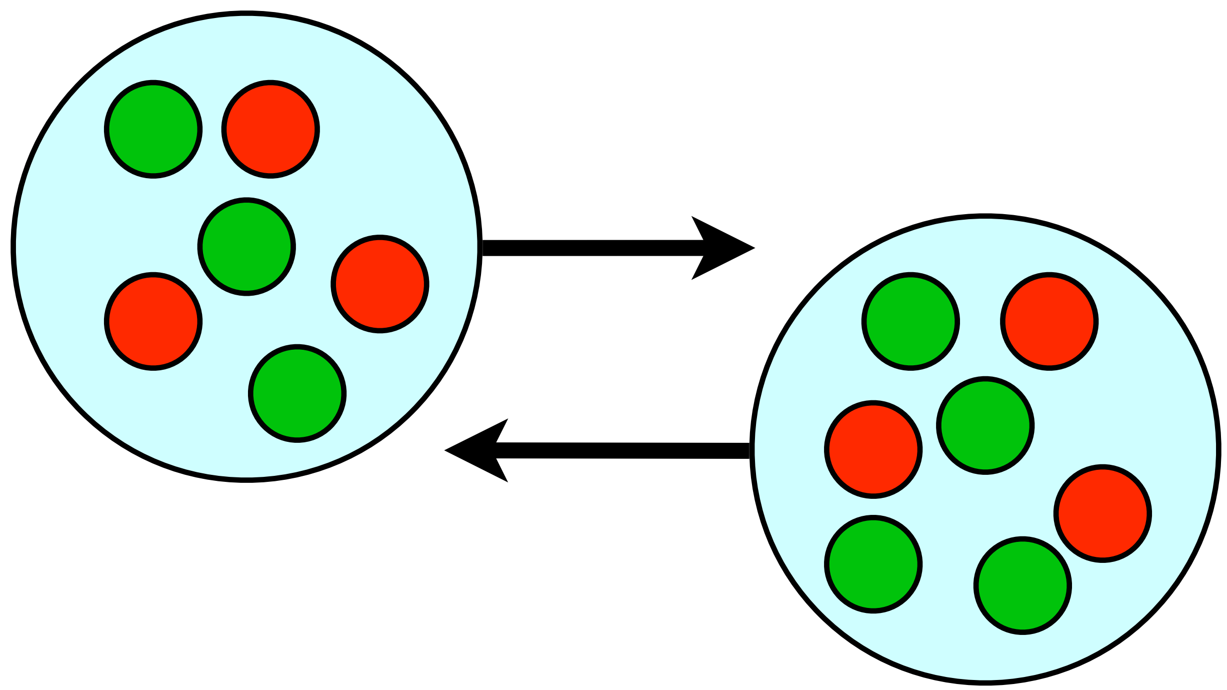
Beam Focus

Beams are 0.03 mm in diameter at interaction point
Eye of needle = 0.3 mm in diameter



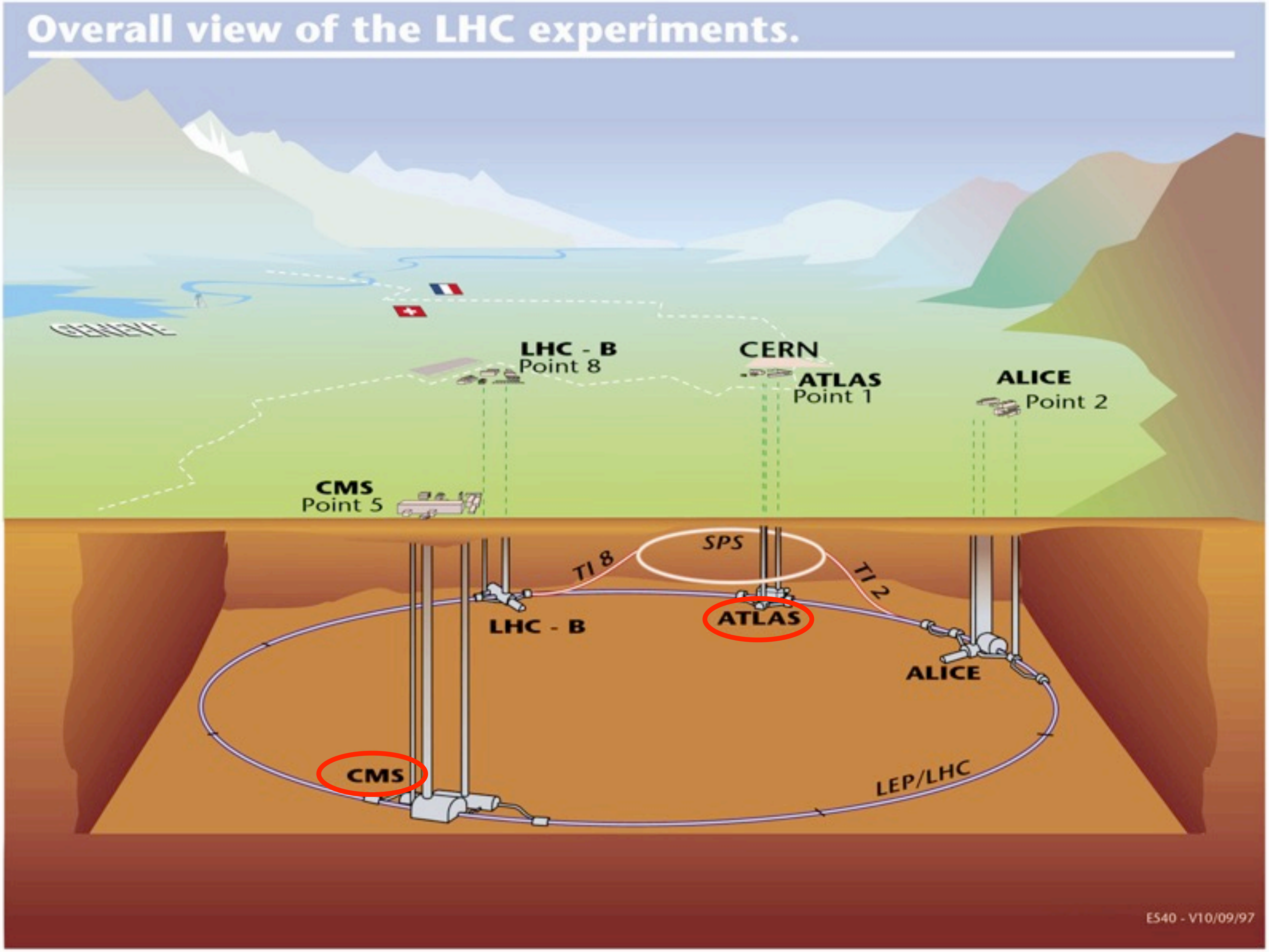
Particle Collisions at LHC

- Protons consist of partons - quarks and gluons

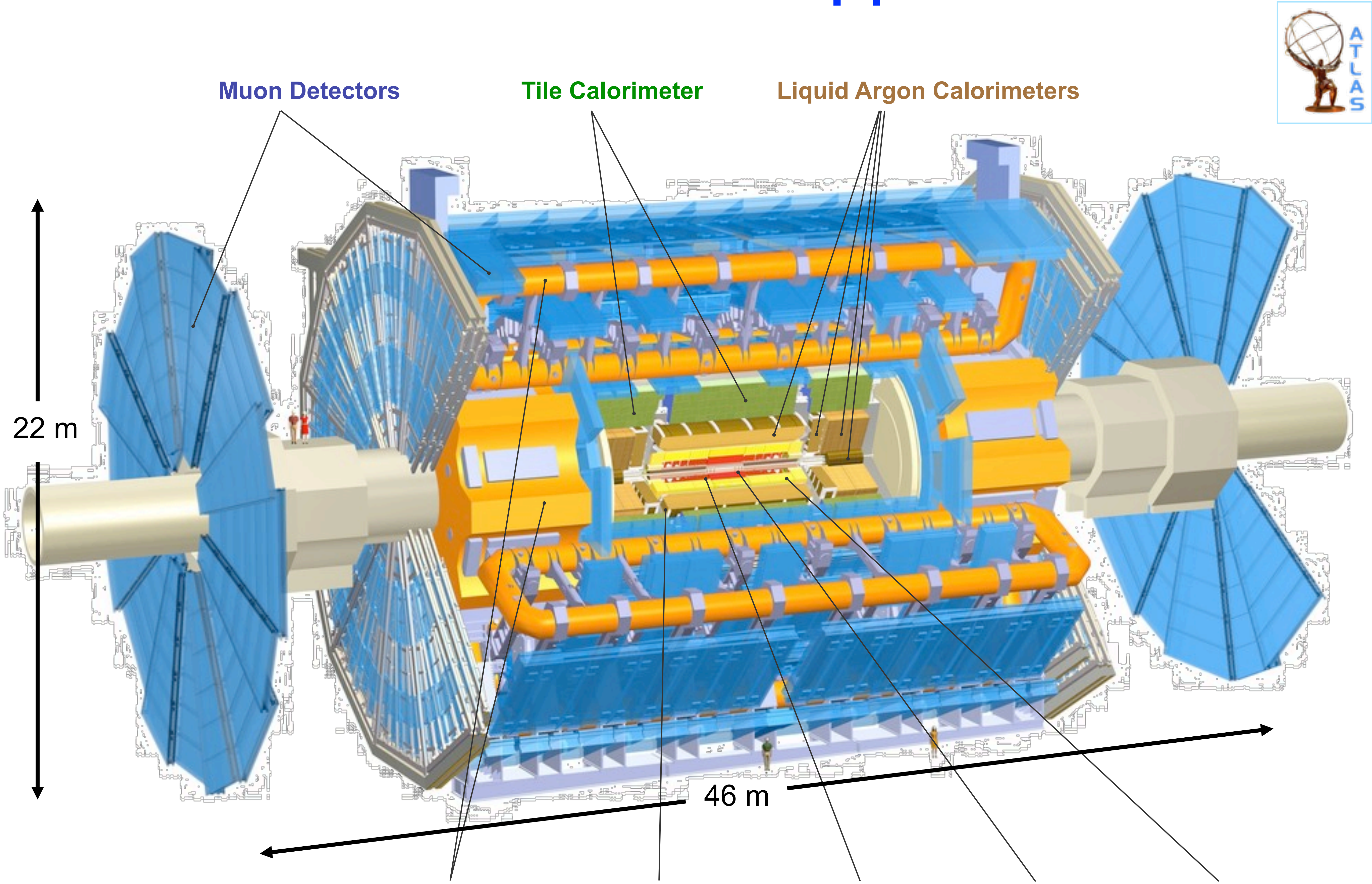


- Event rate = Luminosity x Cross section $(L \times \sigma)$
  - ♦ L=10^{34} cm^{-2}s^{-1} ➡ 1 event/sec for σ= 10^{-34}cm^2 (100 pb)
  - ♦ Integrated luminosity (2011) ~6 fb^{-1}

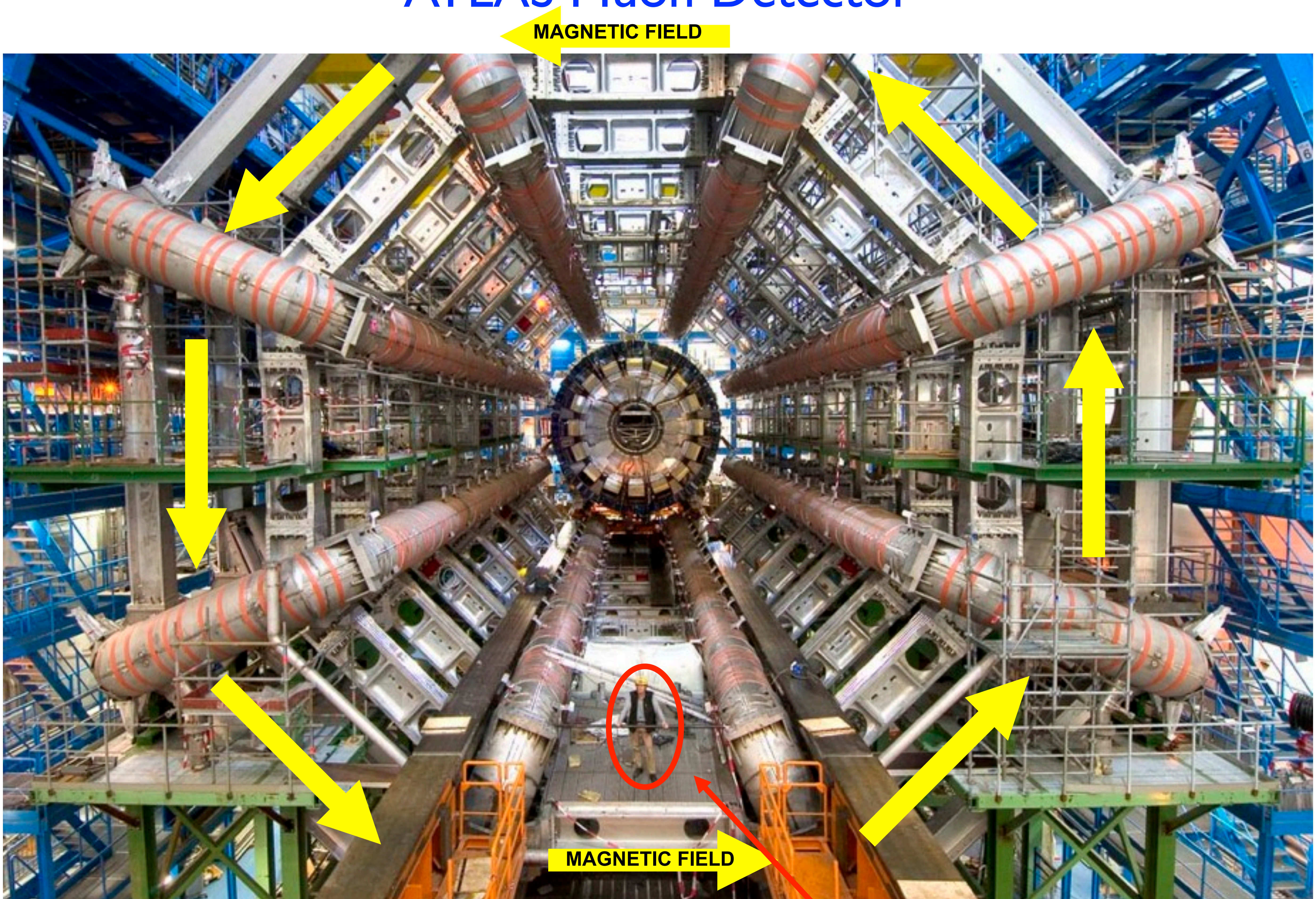
LHC Experiments



A Toroidal LHC ApparatuS



ATLAS Muon Detector

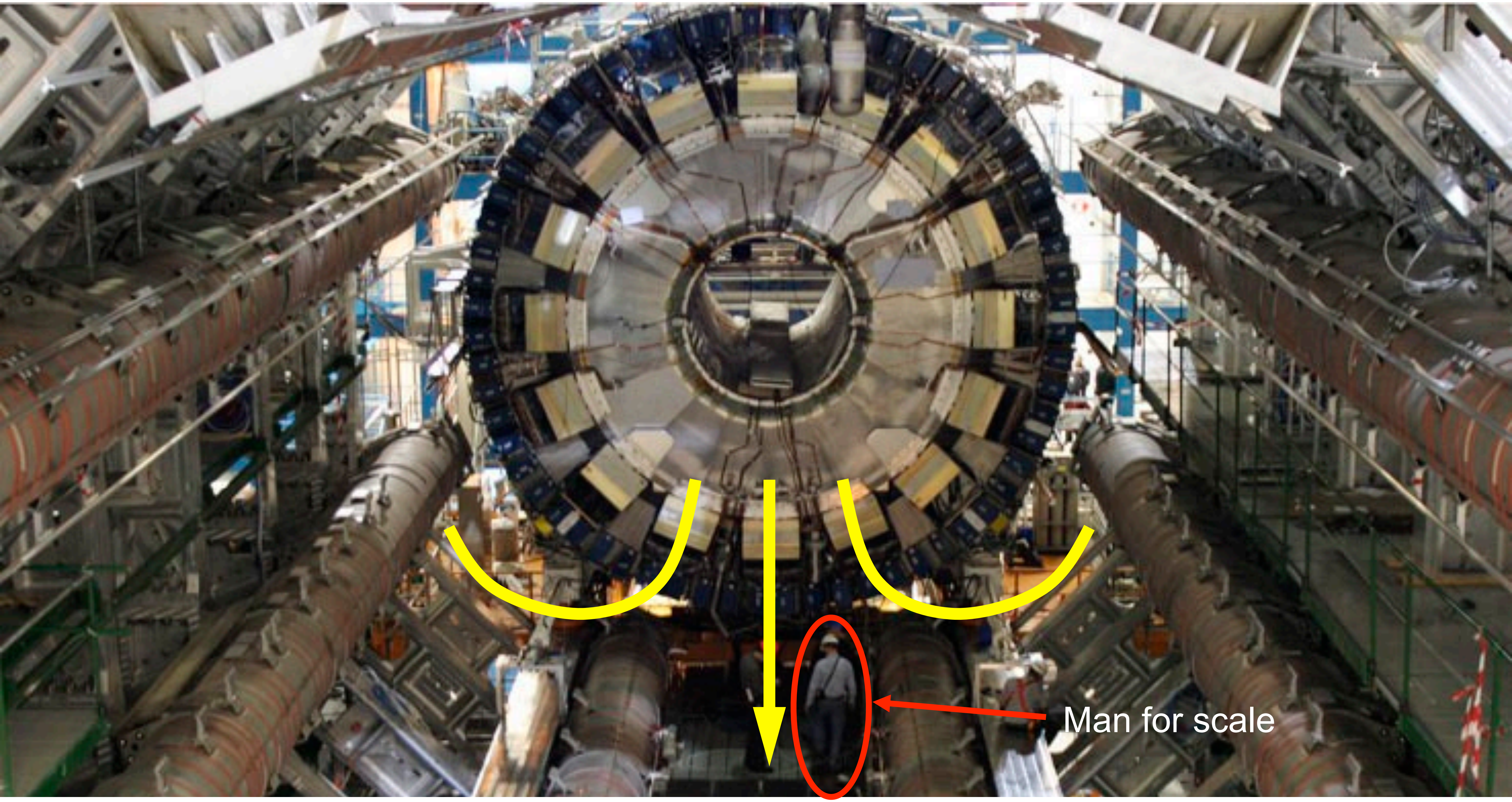


Muons bend away from us.

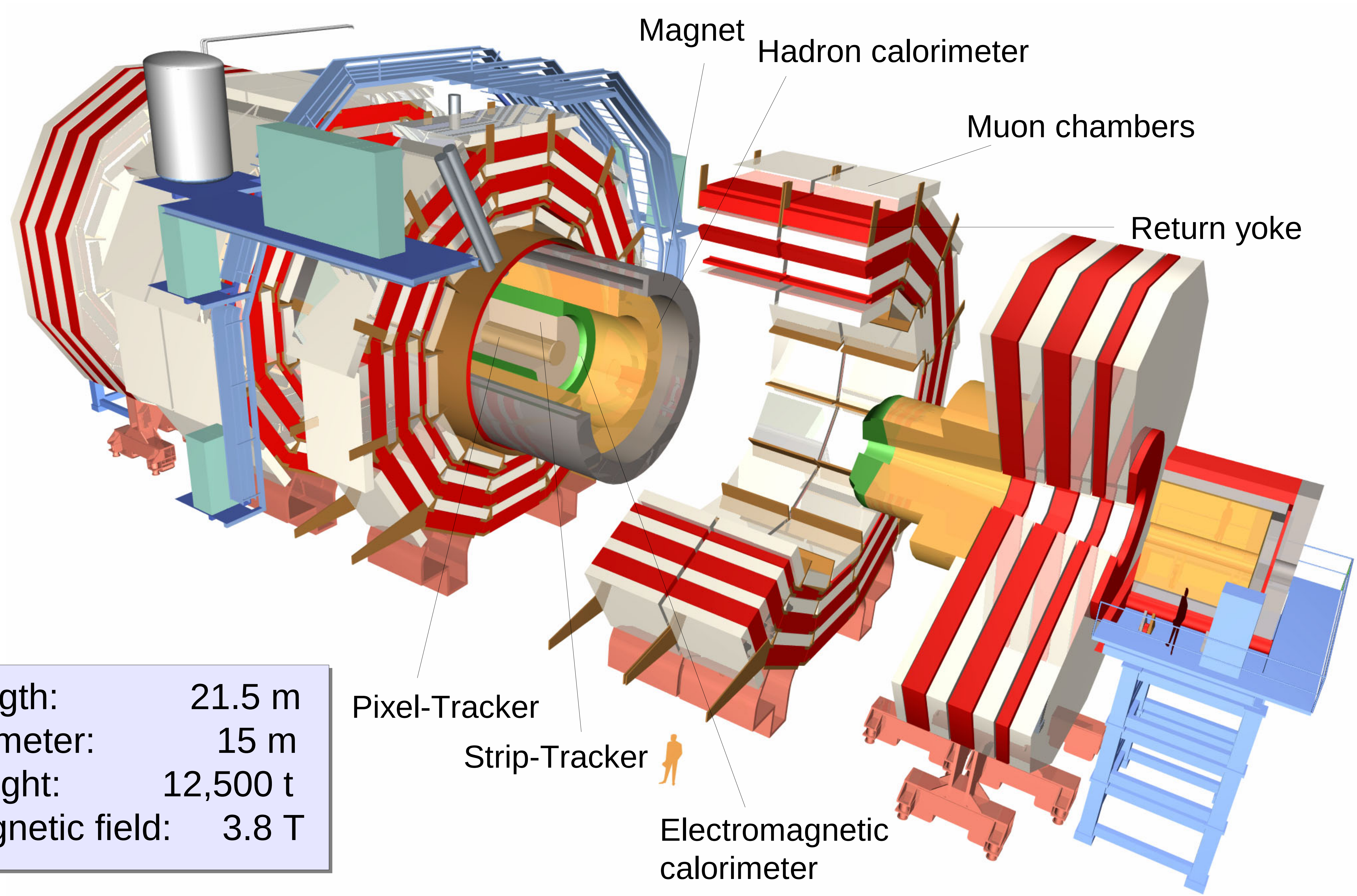
Anti-muons bend toward us.

Man for scale

ATLAS Calorimeters and Central Solenoid



Compact Muon Solenoid



Length:	21.5 m
Diameter:	15 m
Weight:	12,500 t
Magnetic field:	3.8 T

Tevatron Collider

- Located at Fermilab near Chicago
- Proton-antiproton collisions at 1.96 TeV
- Main experiments CDF and D0
- Closed September 2011

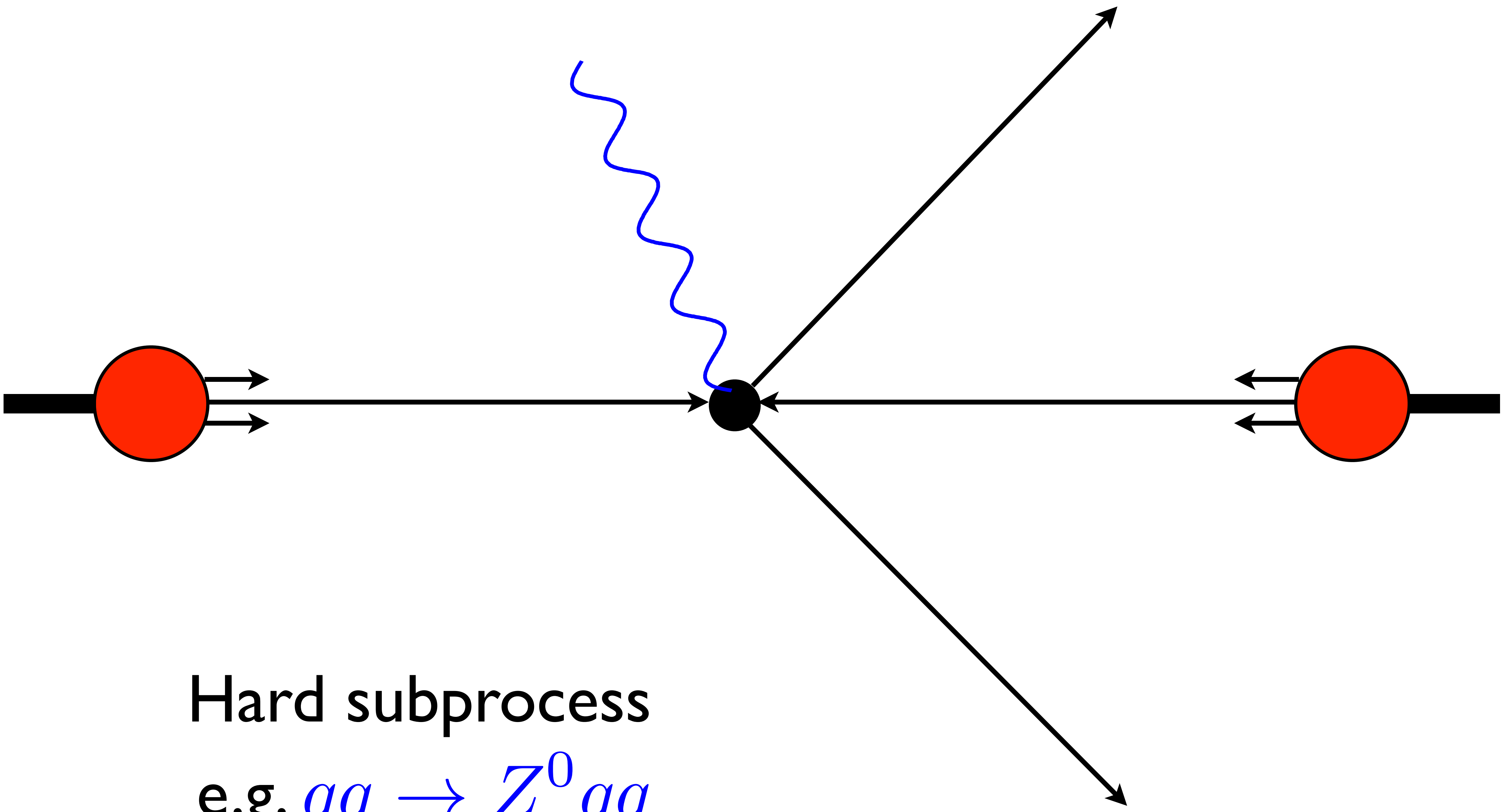
Monte Carlo
Event Generation

Monte Carlo Event Generators

- Traditionally (imprecise) general-purpose tools

- Much recent work to make them more precise

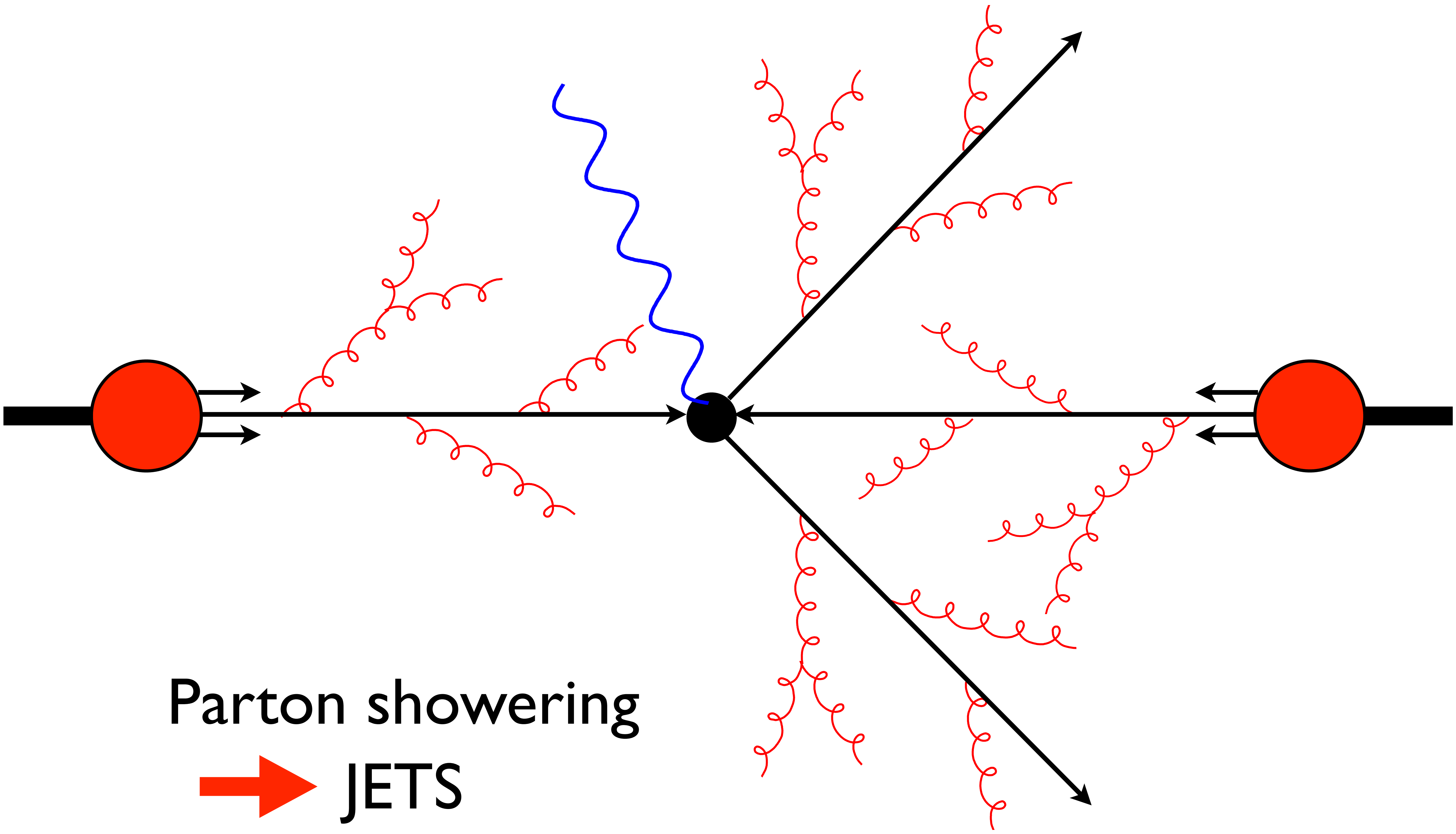
LHC Event Simulation



Hard subprocess

e.g. $qq \to Z^0 qq$

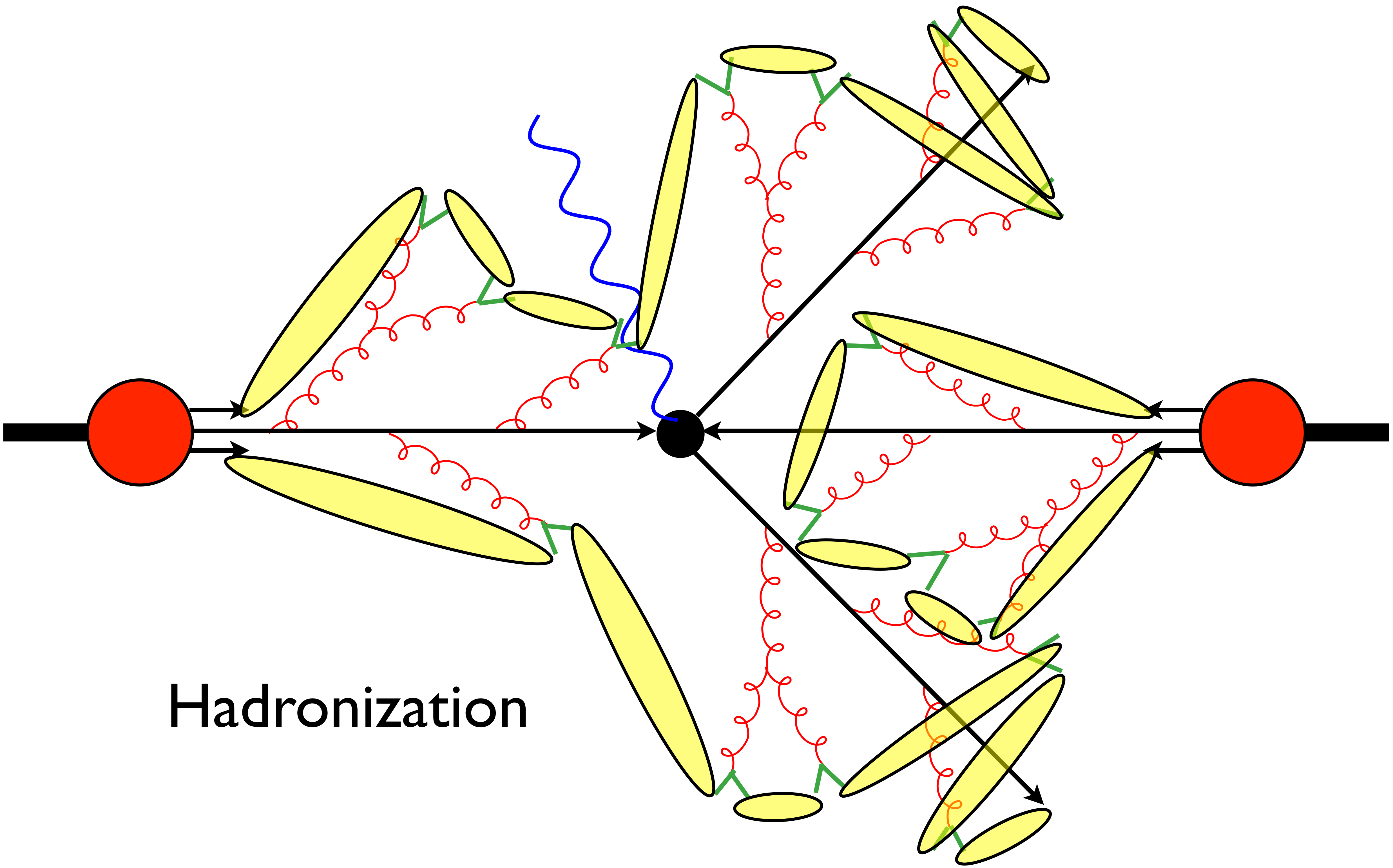
LHC Event Simulation



Parton showering

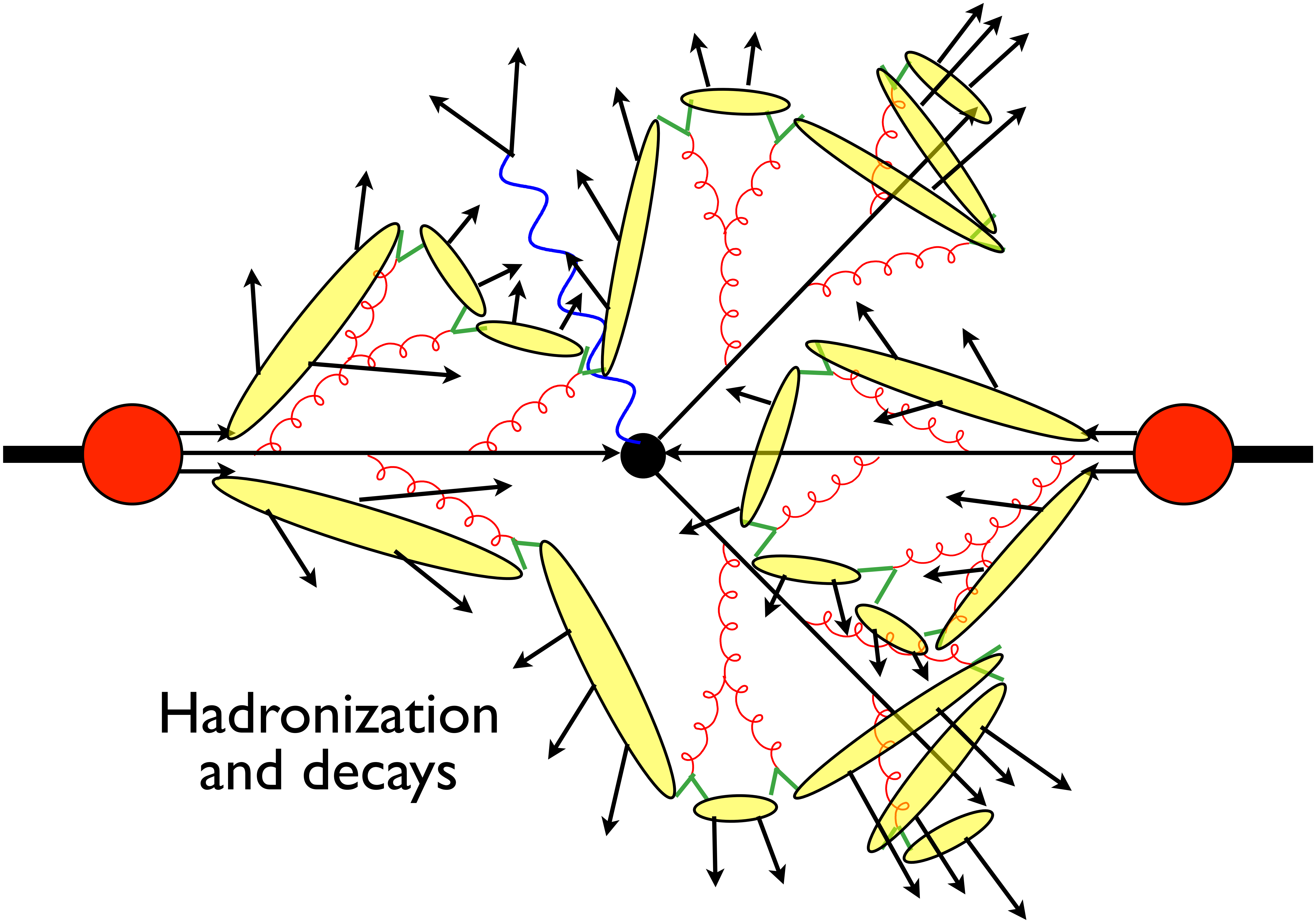
→ JETS

LHC Event Simulation



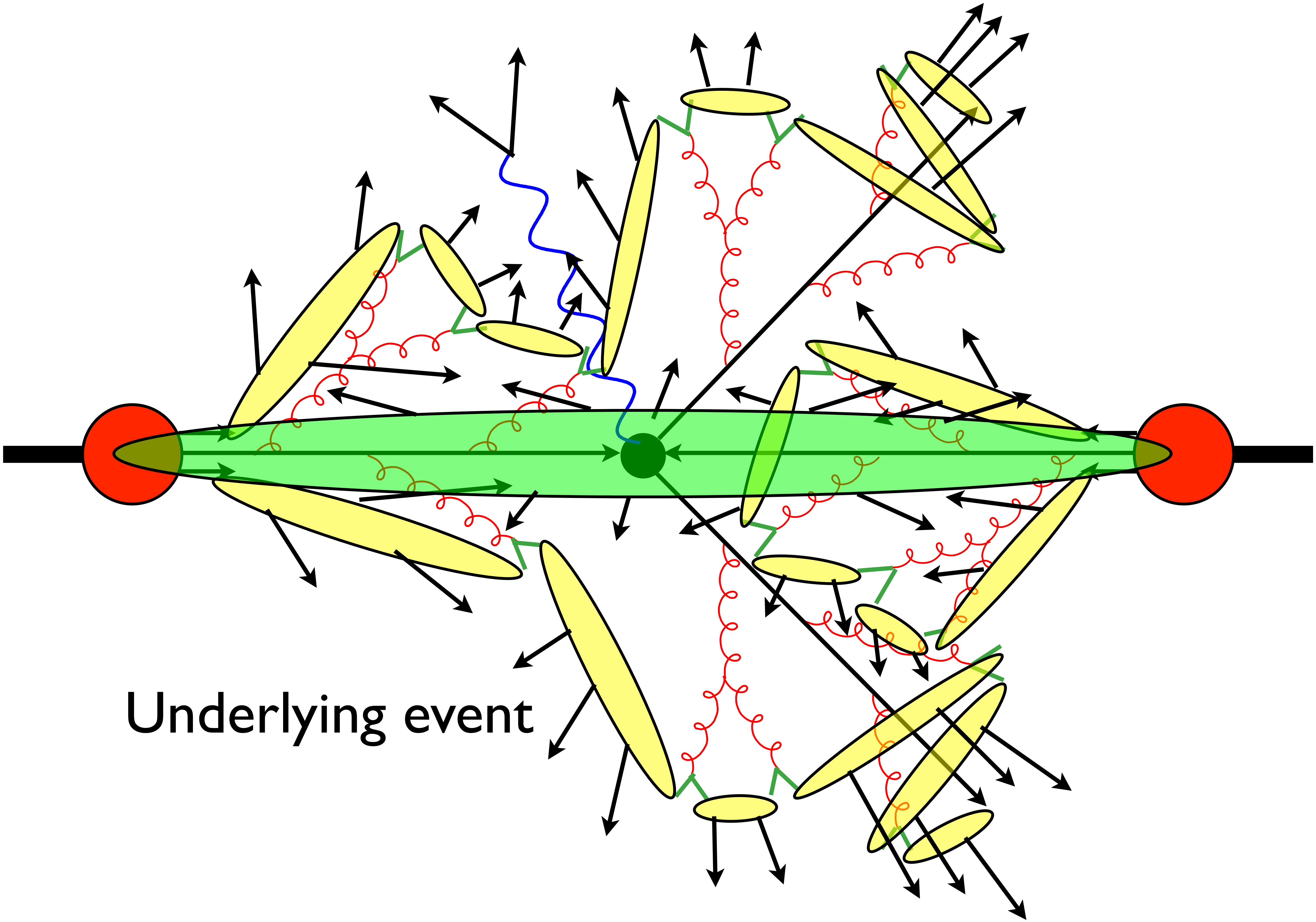
Hadronization

LHC Event Simulation



Hadronization and decays

LHC Event Simulation



Underlying event

MC Event Generators

- **HERWIG** http://projects.hepforge.org/herwig/
  - ➡ Angular-ordered parton shower, cluster hadronization
  - ➡ v6 Fortran; Herwig++
- **PYTHIA** http://www.thep.lu.se/~torbjorn/Pythia.html
  - ➡ Dipole-type parton shower, string hadronization
  - ➡ v6 Fortran; v8 C++
- **SHERPA** http://projects.hepforge.org/sherpa/
  - ➡ Dipole-type parton shower, cluster hadronization
  - ➡ C++

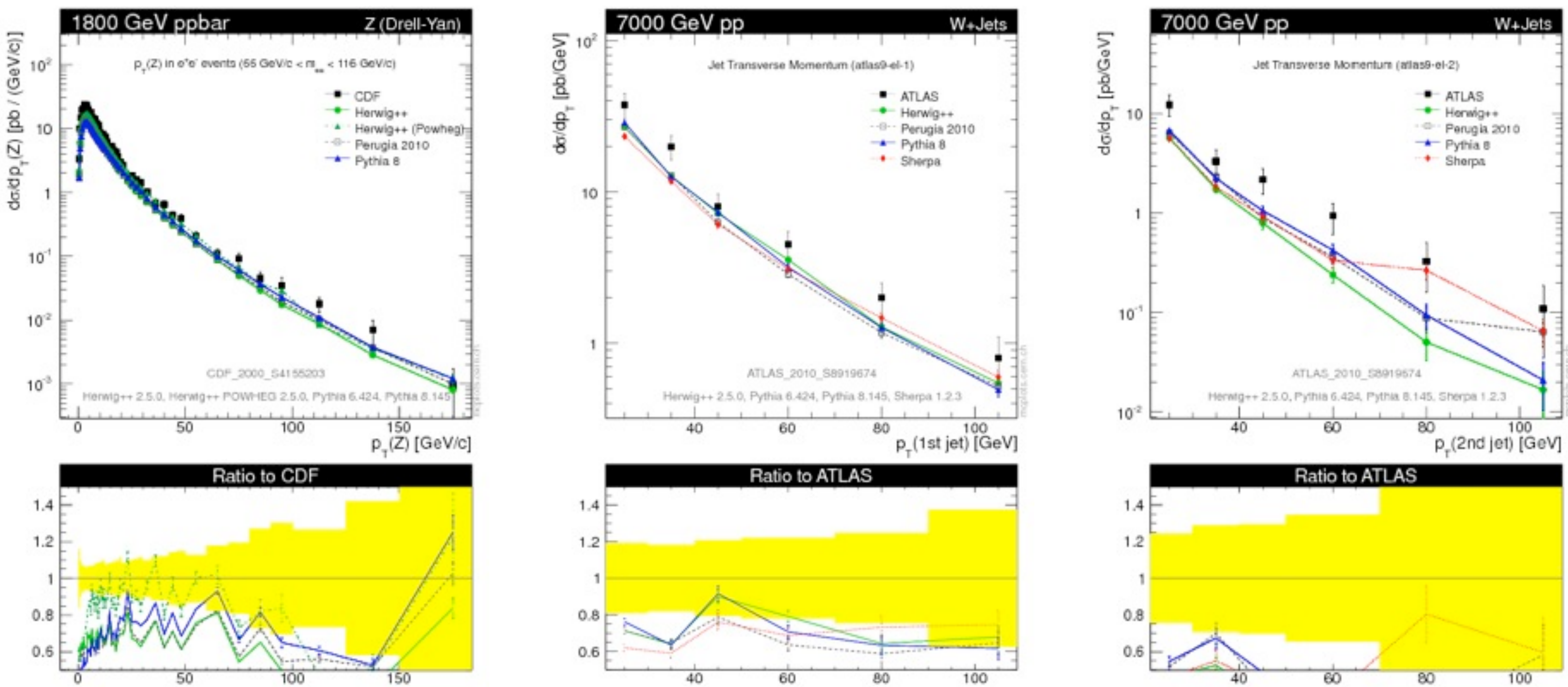
"General-purpose event generators for LHC physics",
A Buckley et al., arXiv:1101.2599, Phys. Rept. 504(2011)145

Parton Shower Monte Carlo

- Hard subprocess: $q\bar{q} \to Z^0$

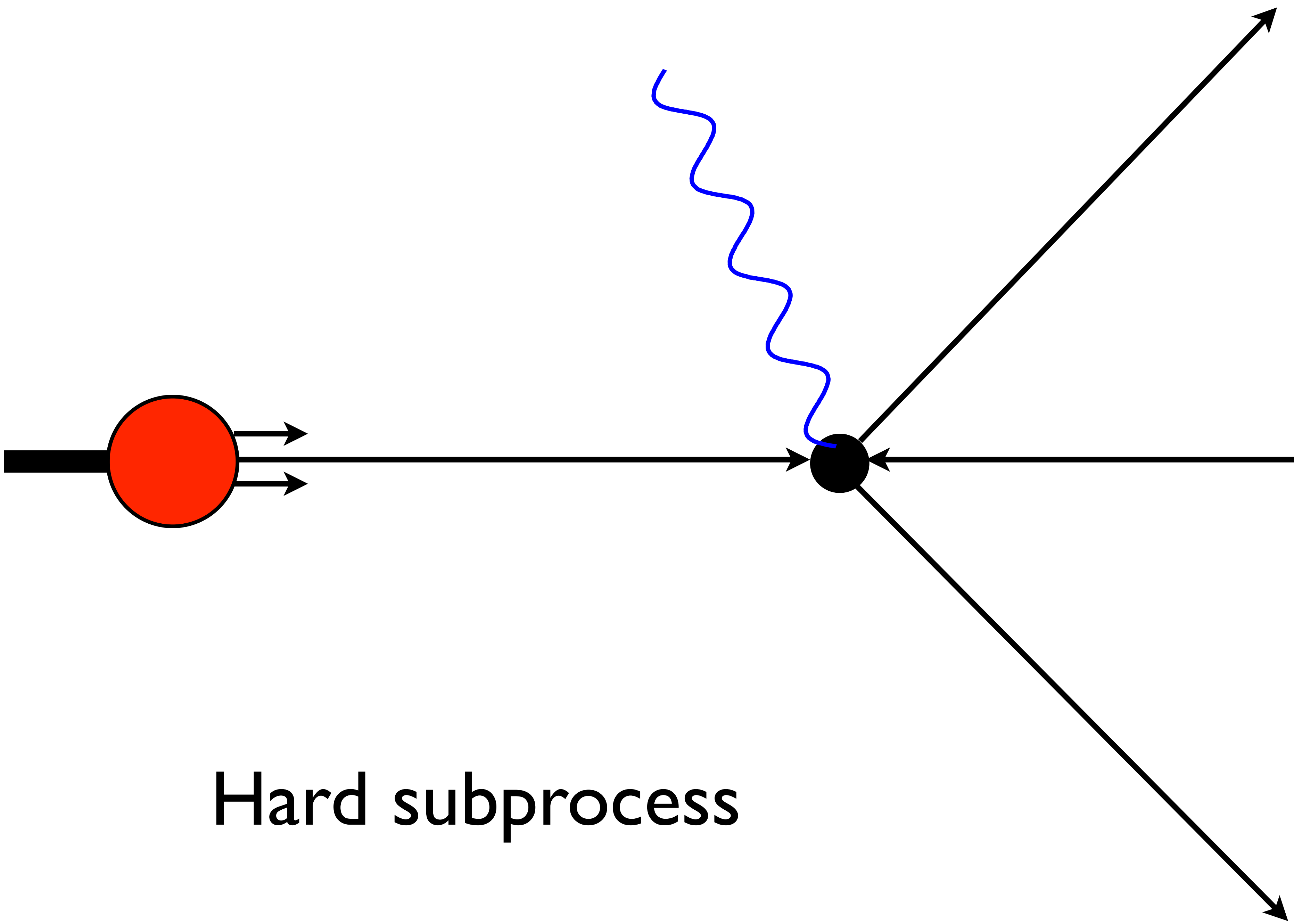
http://mcplots.cern.ch/

http://lhcathome.web.cern.ch/



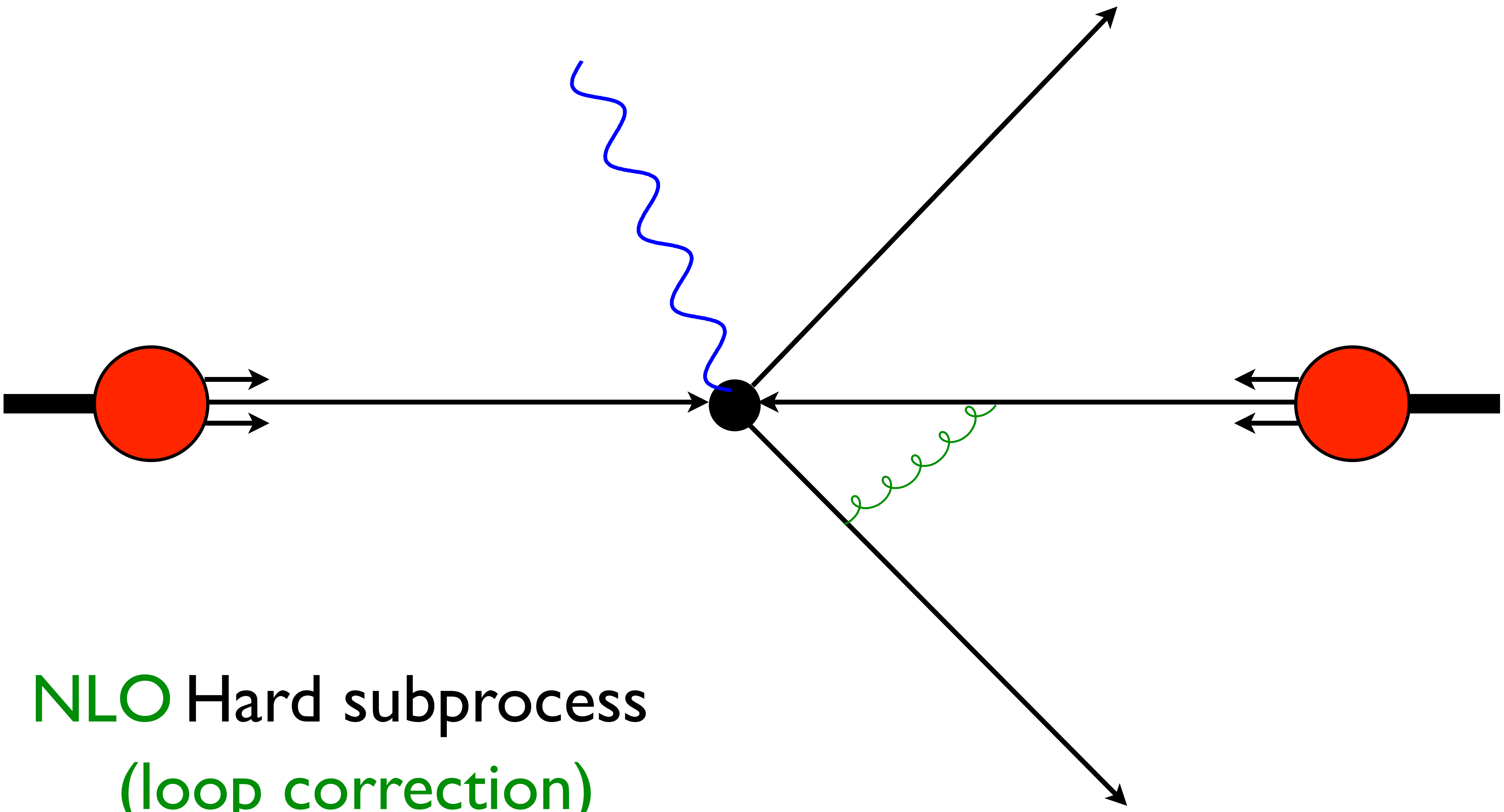
- Leading-order (LO) normalization ➡ need next-to-LO (NLO)
- Worse for high p_T and/or extra jets ➡ need multijet merging

Improving Event Simulation



Hard subprocess

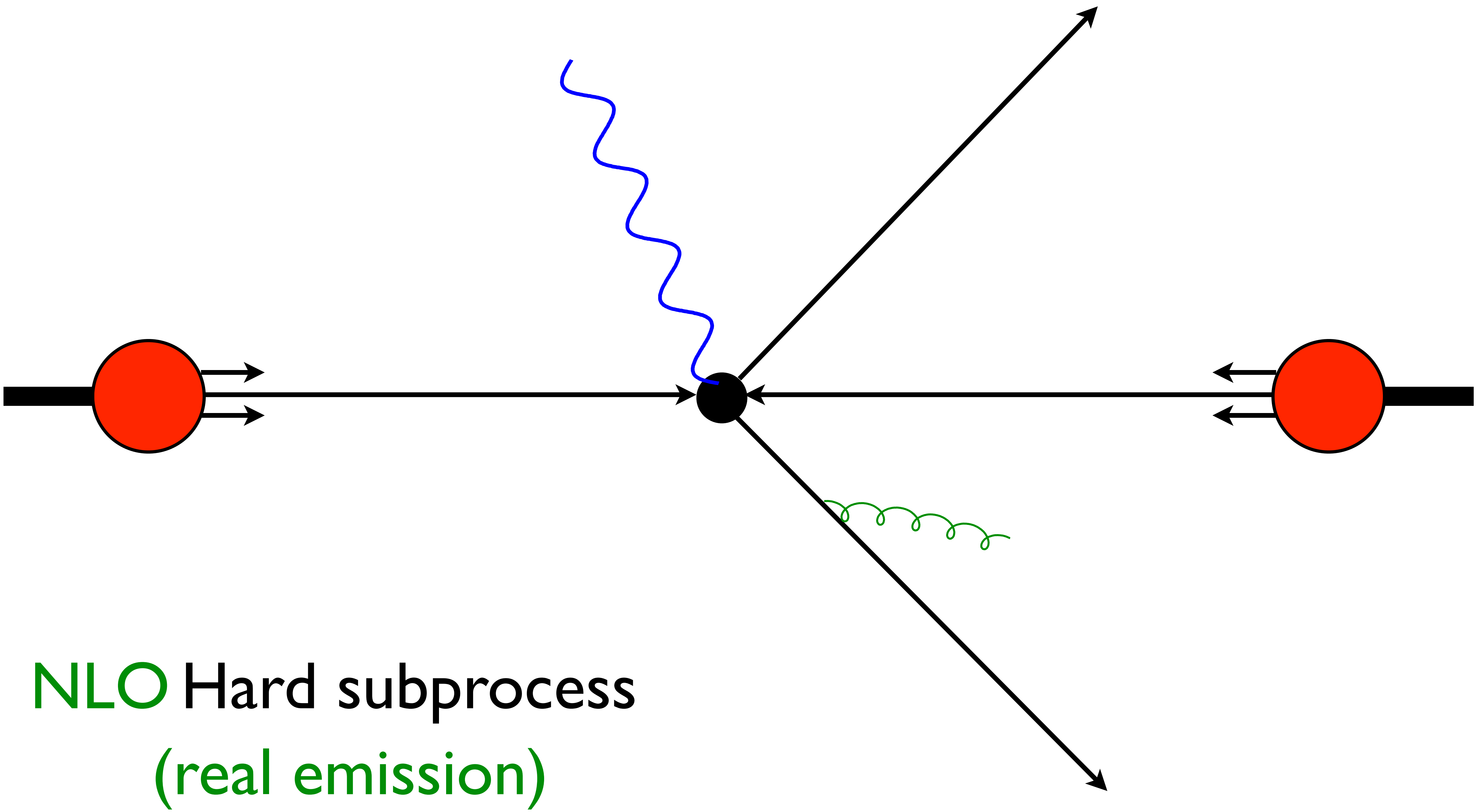
Improving Event Simulation



NLO Hard subprocess

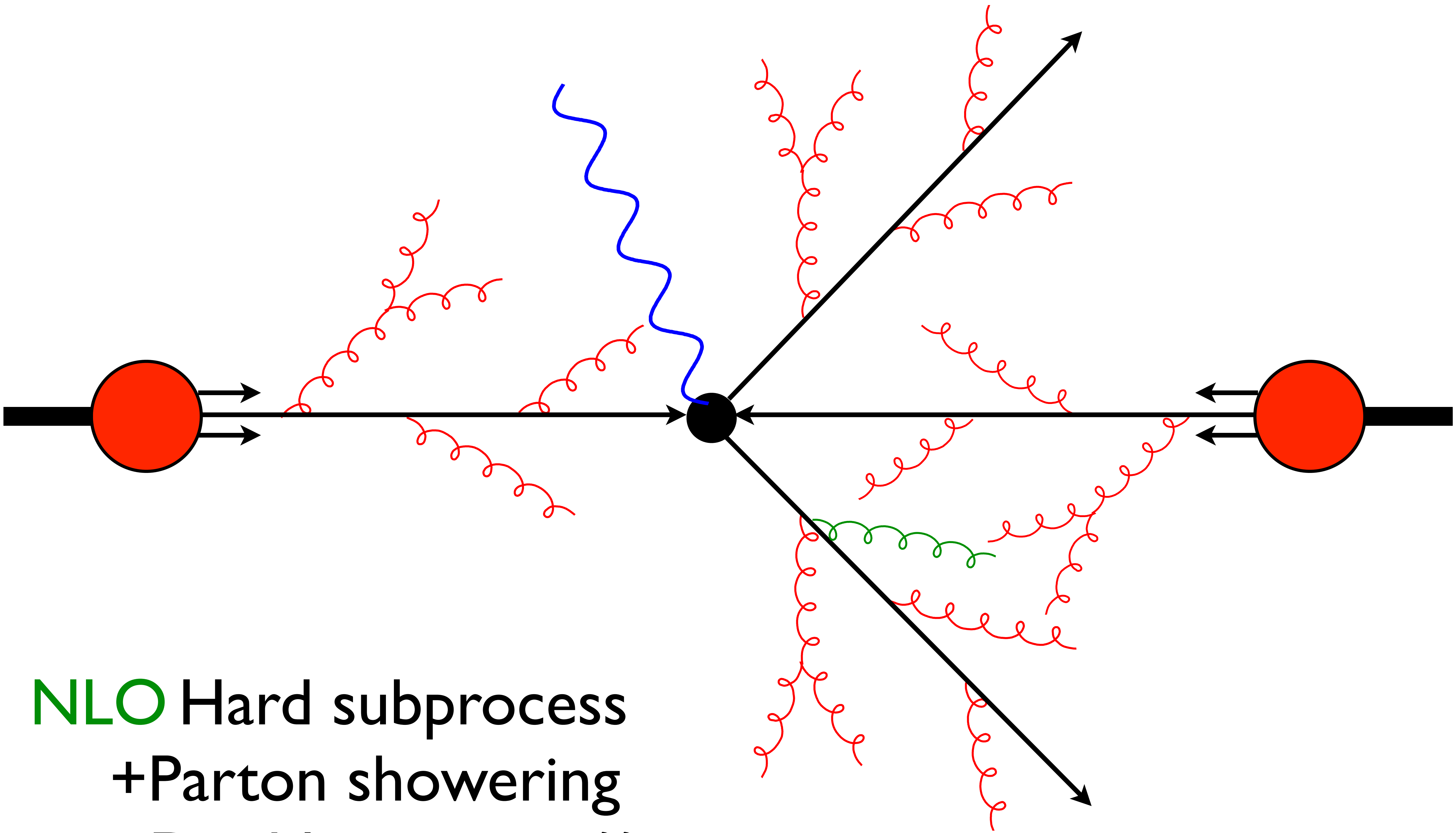
(loop correction)

Improving Event Simulation



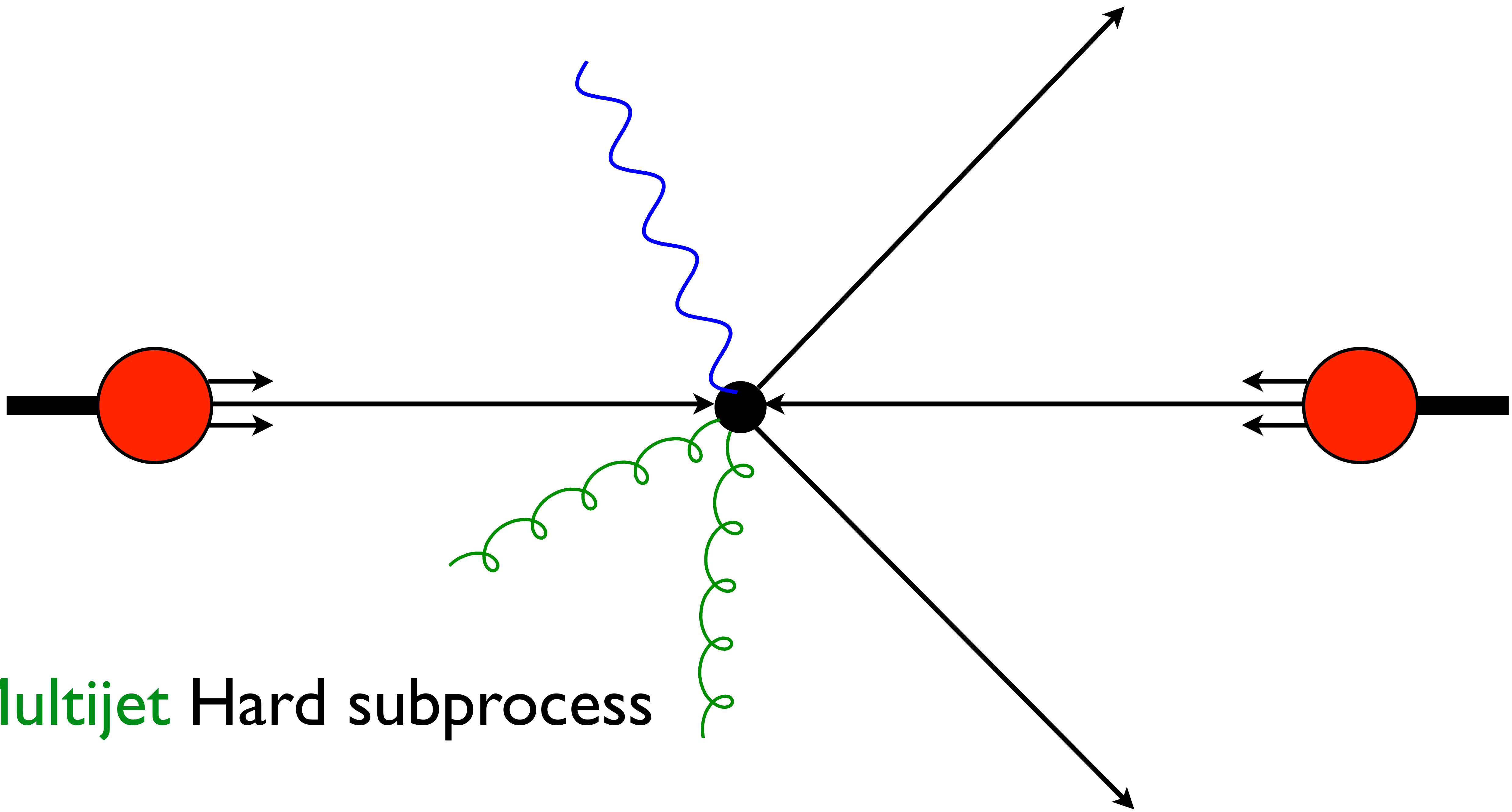
NLO Hard subprocess
(real emission)

Improving Event Simulation



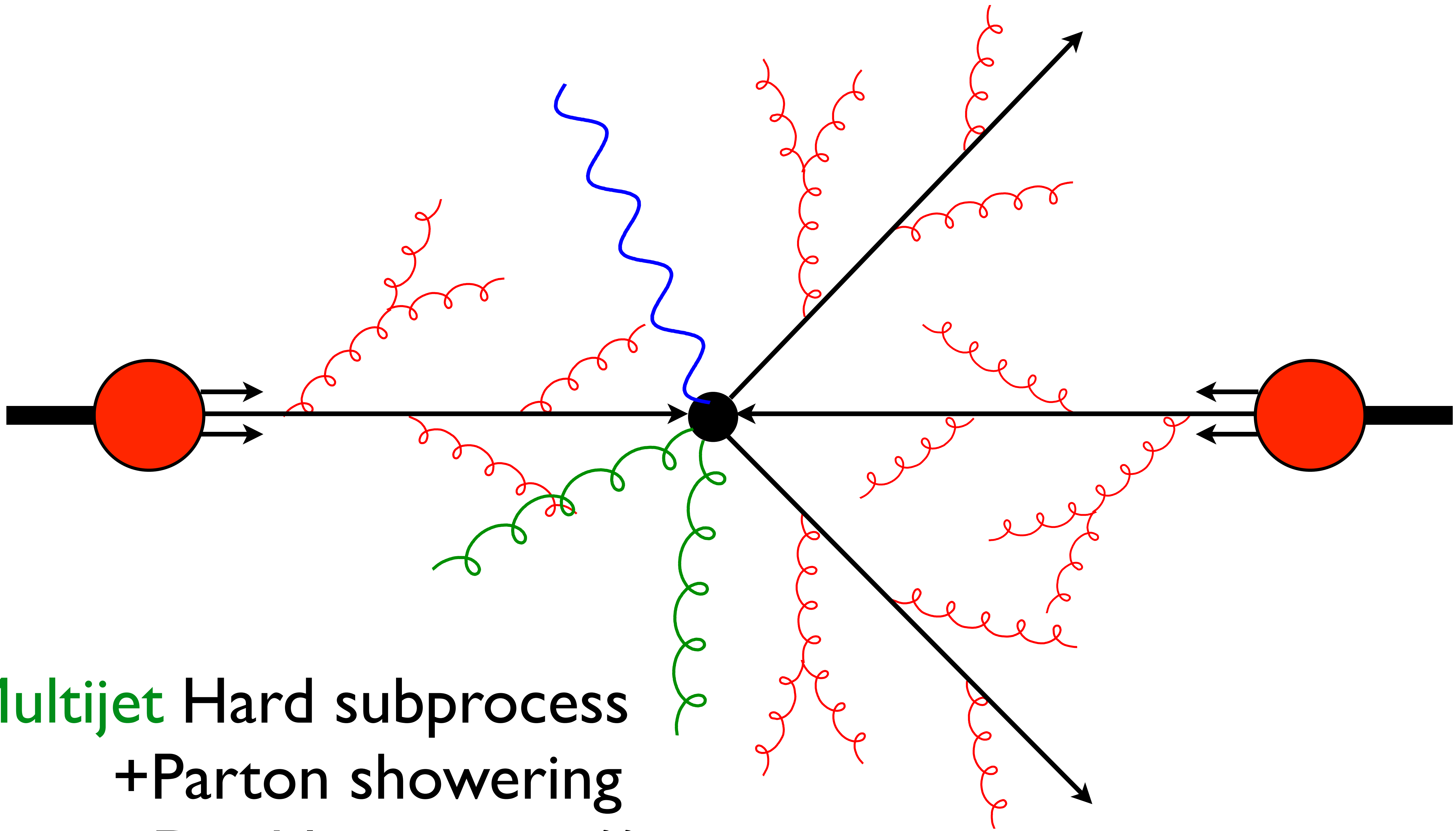
NLO Hard subprocess
+Parton showering
= Double counting??

Improving Event Simulation



Multijet Hard subprocess

Improving Event Simulation



Multijet Hard subprocess
+Parton showering
= Double counting??

Matching & Merging

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  - MC@NLO — Frixione, BW, 2002
  - POWHEG — Nason, 2004
- Merging parton showers with LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW — Catani, Krauss, Kühn, BW, 2001
  - Dipole — Lönnblad, 2001
  - MLM merging — Mangano, 2002

MC@NLO matching

finite virtual — divergent

$$d\sigma_{\rm NLO} = \left[B(\Phi_B) + V(\Phi_B) - \int \sum_i C_i(\Phi_B,\Phi_R)\, d\Phi_R\right] d\Phi_B + R(\Phi_B,\Phi_R)\, d\Phi_B\, d\Phi_R$$

$$\equiv \left[B + V - \int C\, d\Phi_R\right] d\Phi_B + R\, d\Phi_B\, d\Phi_R$$

$$d\sigma_{\rm MC} = B(\Phi_B)\, d\Phi_B \left[\Delta_{\rm MC}(0) + \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)} \Delta_{\rm MC}(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]$$

$$\equiv B\, d\Phi_B \left[\Delta_{\rm MC}(0) + (R_{\rm MC}/B)\, \Delta_{\rm MC}(k_T)\, d\Phi_R\right]$$

Sudakov factor = P(no emission above p_T) →

$$\Delta_{\rm MC}(p_T) = \exp\left[-\int d\Phi_R \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_B,\Phi_R) - p_T)\right]$$

$$d\sigma_{\rm MC@NLO} = \left[B + V + \int (R_{\rm MC} - C)\, d\Phi_R\right] d\Phi_B \left[\Delta_{\rm MC}(0) + (R_{\rm MC}/B)\, \Delta_{\rm MC}(k_T)\, d\Phi_R\right] + (R - R_{\rm MC})\, \Delta_{\rm MC}(k_T)\, d\Phi_B\, d\Phi_R$$

finite $\gtrless 0$

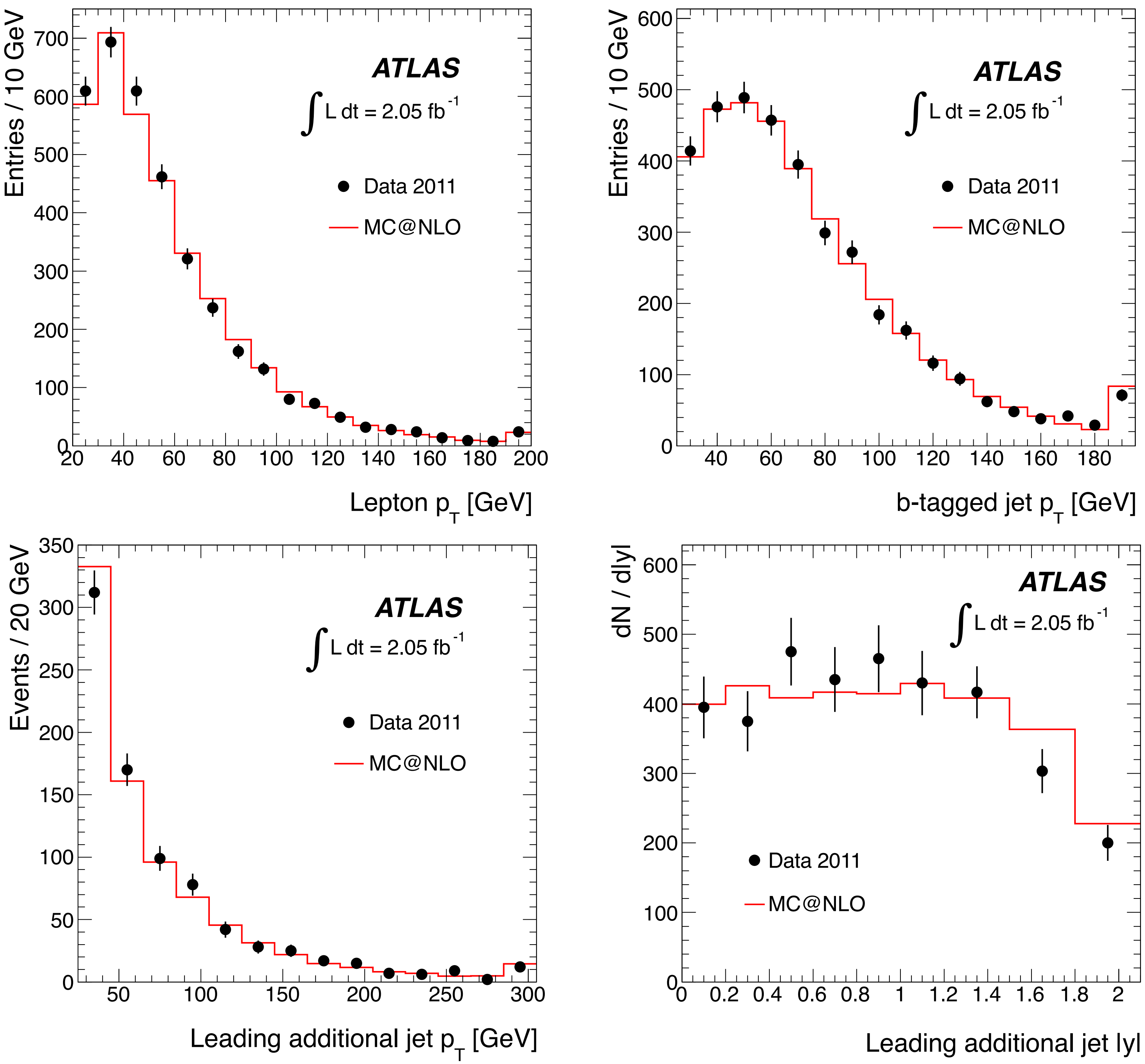
MC starting from one emission

MC starting from no emission

- Expanding gives NLO result

S Frixione & BW, JHEP 06(2002)029

MC@NLO for $t\bar{t}$ at LHC



- Top quark pair production
- ATLAS at LHC (7 TeV)
- p_T is transverse momentum wrt beams
- y is rapidity $\frac{1}{2}\ln\frac{E+p_L}{E-p_L}$
- Both decays leptonic:

$$t\bar{t} \to b\bar{b}l^+l^-\nu\bar{\nu}$$

ATLAS, arXiv:1203.5015

S Frixione, P Nason, BW, JHEP 08(2003)007

POWHEG matching

$$d\sigma_{\rm MC} = B(\Phi_B)\, d\Phi_B \left[\Delta_{\rm MC}(0) + \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)}\Delta_{\rm MC}(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]$$

$$d\sigma_{\rm PH} = \overline{B}(\Phi_B)\, d\Phi_B \left[\Delta_R(0) + \frac{R(\Phi_B,\Phi_R)}{B(\Phi_B)}\Delta_R(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]$$

$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int\left[R(\Phi_B,\Phi_R) - \sum_i C_i(\Phi_B,\Phi_R)\right] d\Phi_R$$

$$\Delta_R(p_T) = \exp\left[-\int d\Phi_R \frac{R(\Phi_B,\Phi_R)}{B(\Phi_B)}\theta(k_T(\Phi_B,\Phi_R) - p_T)\right]$$

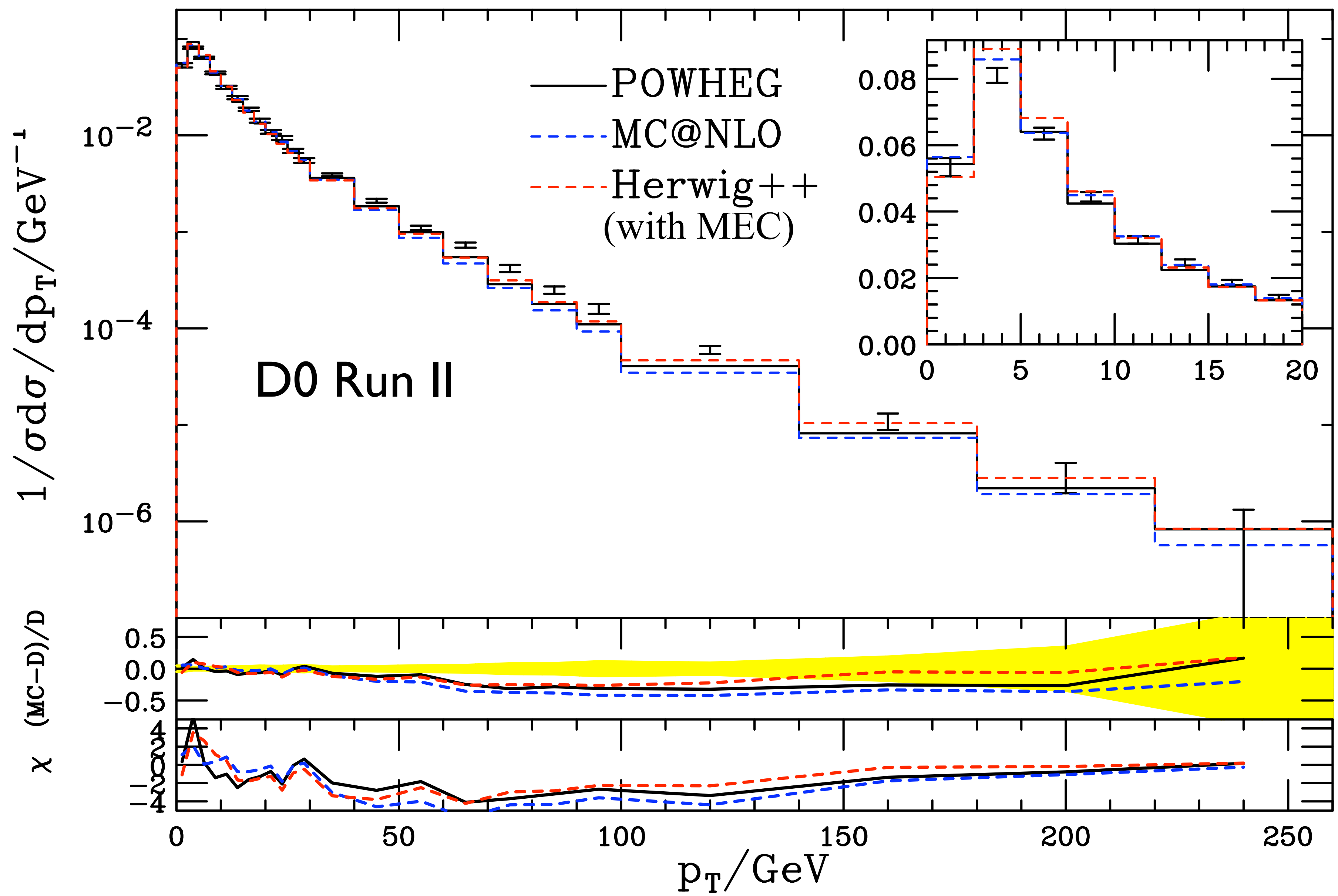
← Use exact R in Sudakov factor for hardest emission

- NLO with (almost) no negative weights
- High p_T always enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_S)$

arbitrary NNLO (→ $\mathcal{O}(\alpha_S)$)

P Nason, JHEP 11(2004)040

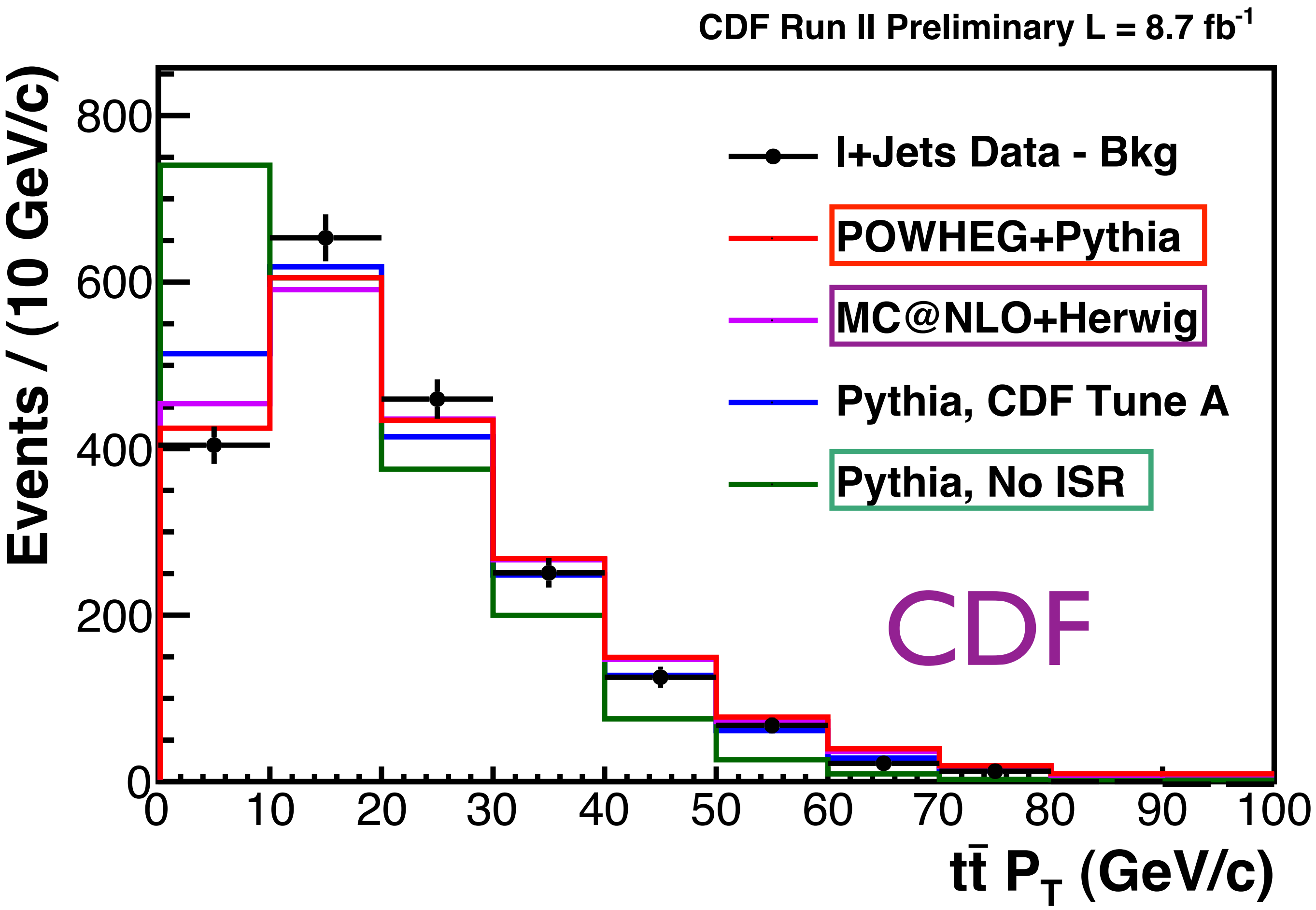
Z^0 p_T at Tevatron

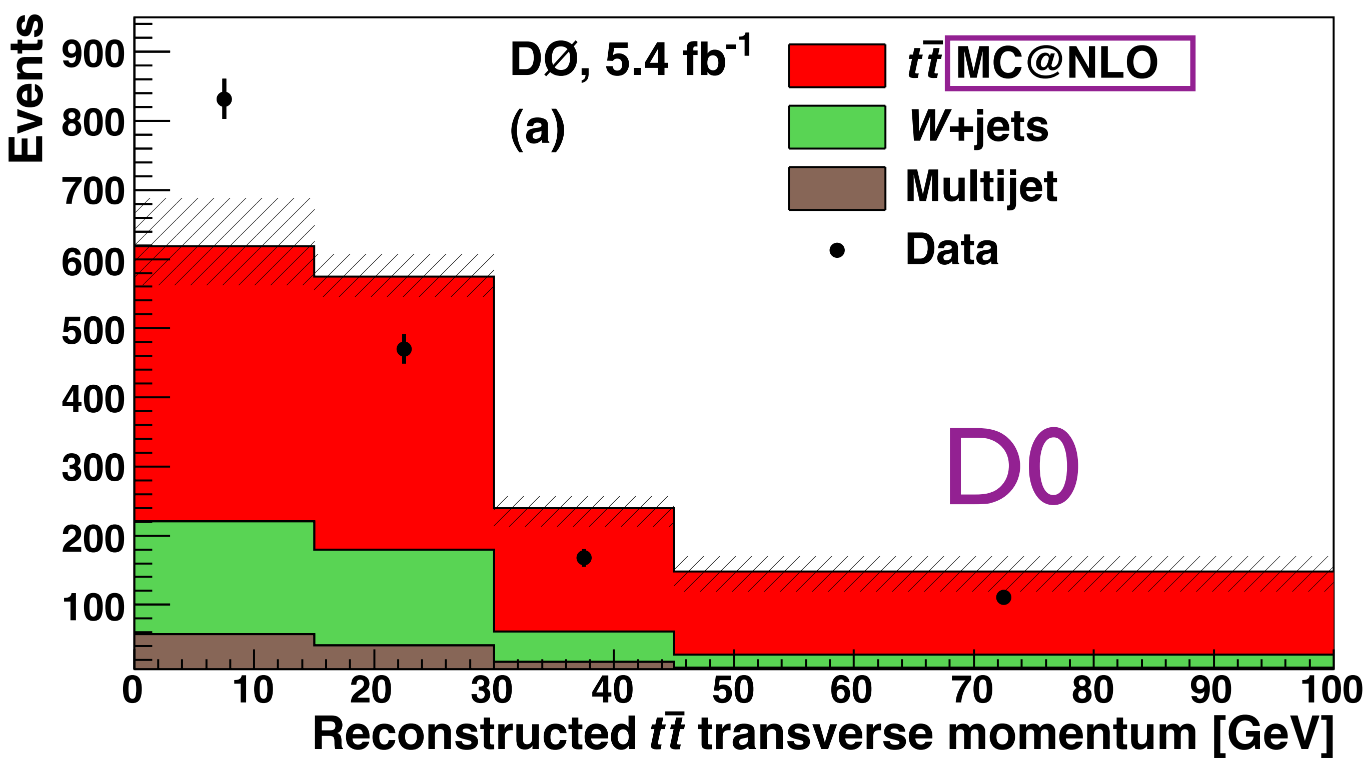


- All agree (tuned) at Tevatron

Hamilton, Richardson, Tully JHEP10(2008)015

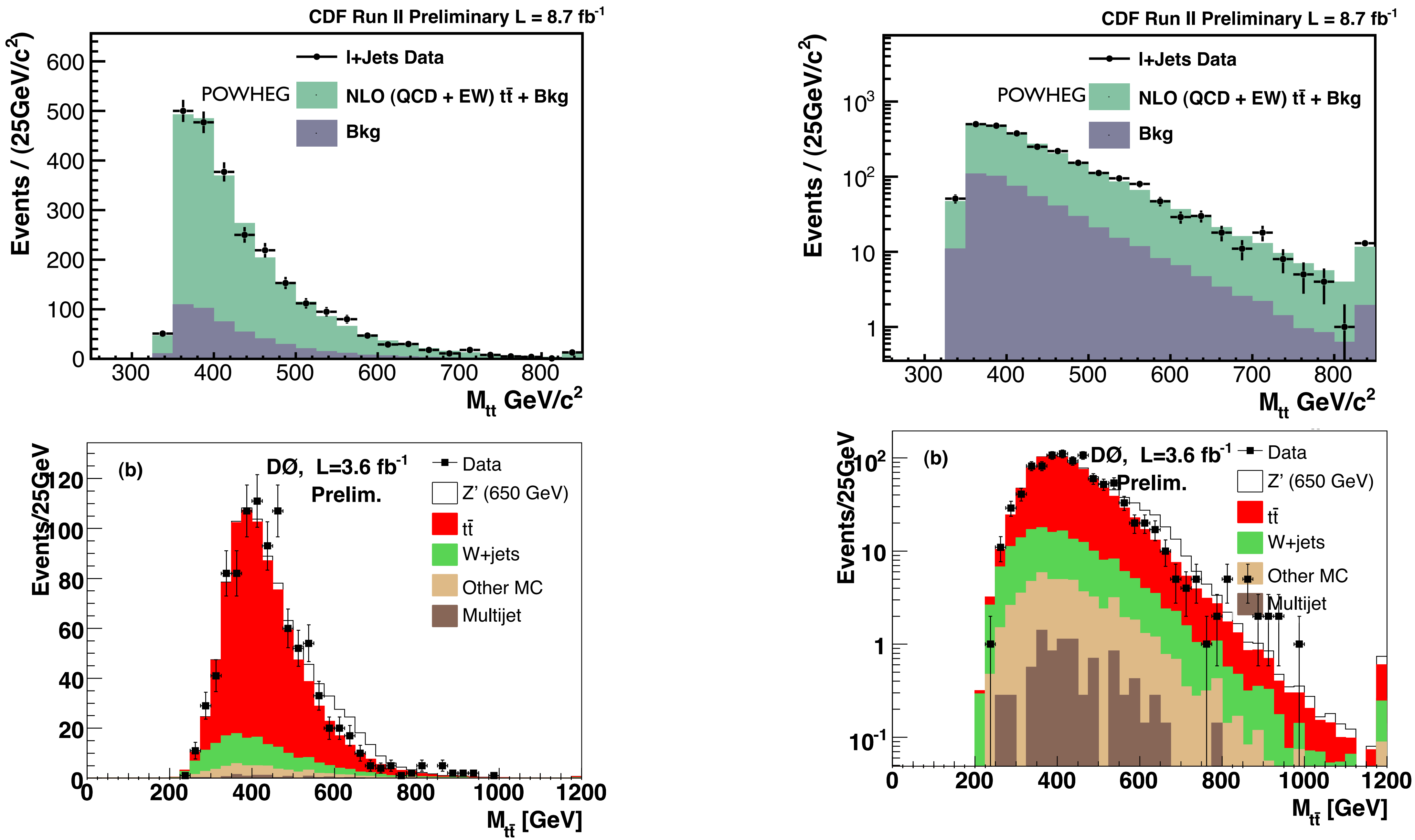
$t\bar{t}$ p_T at Tevatron





- CDF and D0 disagree
- CDF agrees with Standard Model

$t\bar{t}$ inv. mass at Tevatron



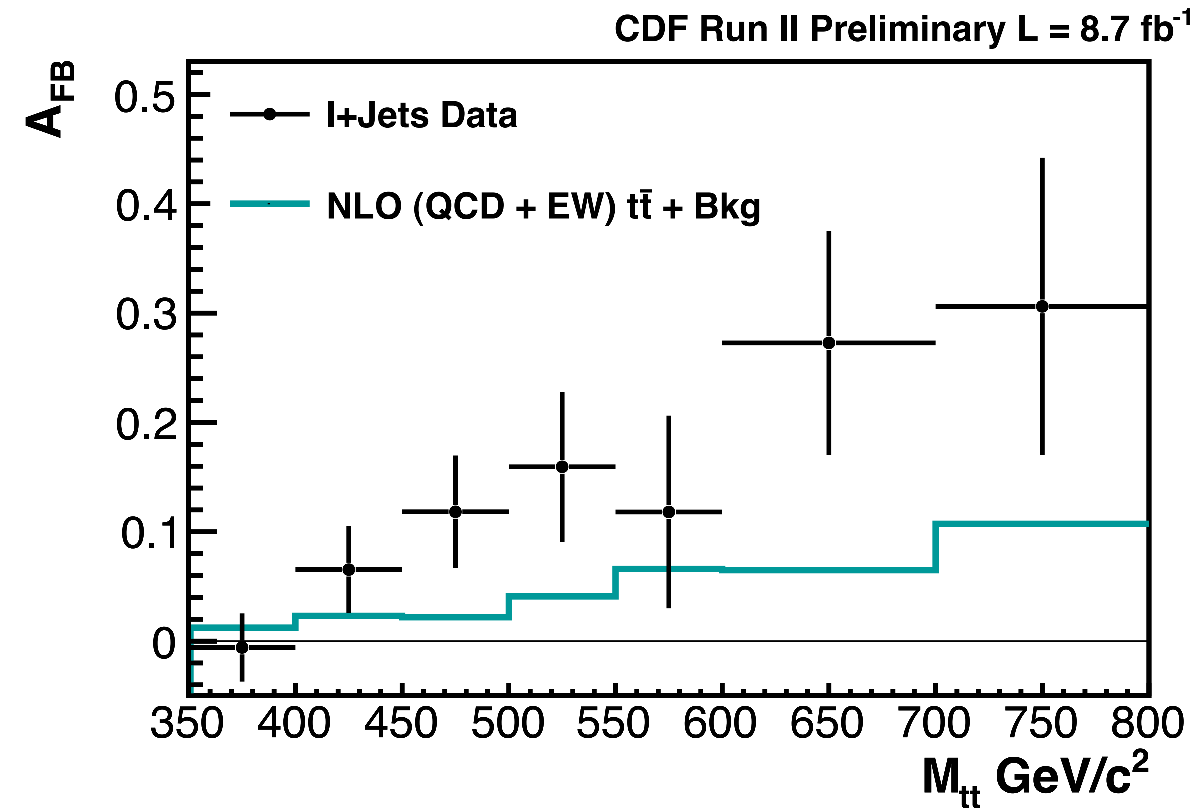
- Good place to look for new particles
- CDF & D0 agree with SM, but ...

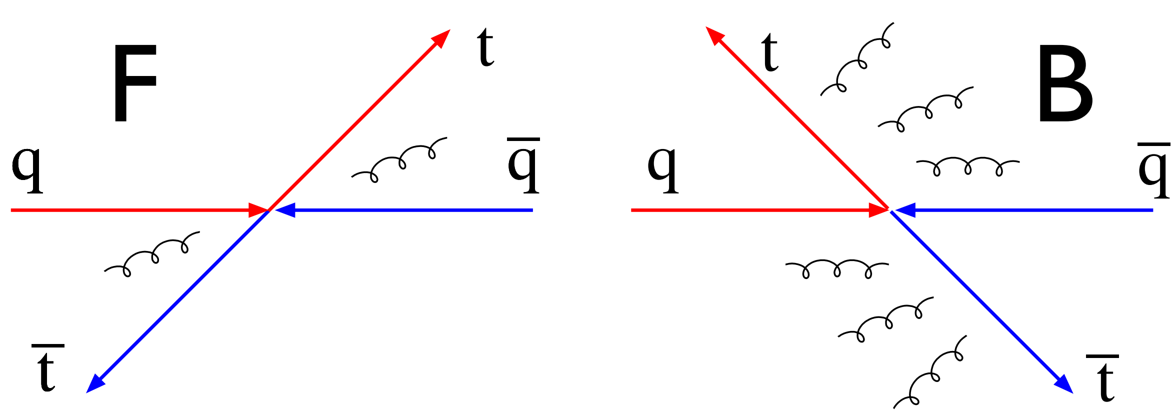
$t\bar{t}$ A_{FB} at Tevatron

$$A_{\rm FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

	MC@NLO	POWHEG	MCFM
Inclusive	0.067	0.066	0.073
$\lvert\Delta y\rvert < 1$	0.047	0.043	0.049
$\lvert\Delta y\rvert > 1$	0.130	0.139	0.150
$M_{t\bar{t}} < 450$ GeV/c^2	0.054	0.047	0.050
$M_{t\bar{t}} > 450$ GeV/c^2	0.089	0.100	0.110





- SM disagreement??

$t\bar{t}$ A_{FB} at Tevatron

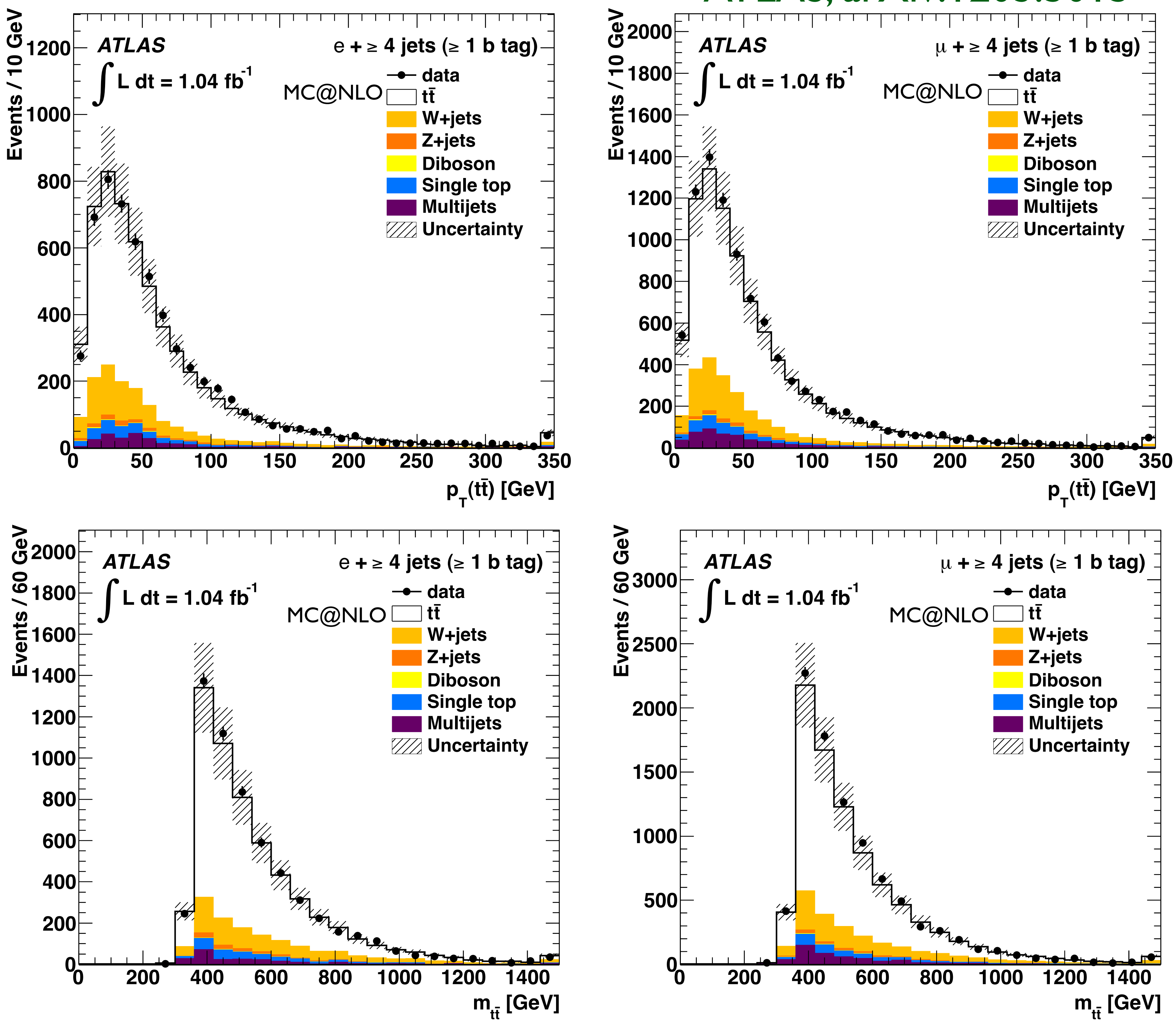
Selection	NLO (QCD+EW)	CDF, 5.3 fb^{-1}	D0, 5.4 fb^{-1}	CDF, 8.7 fb-1
Inclusive	6.6	15.8 ± 7.4	19.6 ± 6.5	16.2 ± 4.7
M_{tt} < 450 GeV/c^2	4.7	−11.6 ± 15.3	7.8 ± 4.8 (Bkg. Subtracted)	7.8 ± 5.4
M_{tt} ≥ 450 GeV/c^2	10.0	47.5 ± 11.2	11.5 ± 6.0 (Bkg. Subtracted)	29.6 ± 6.7
$\|\Delta y\|$ < 1.0	4.3	2.6 ± 11.8	6.1 ± 4.1 (Bkg. Subtracted)	8.8 ± 4.7
$\|\Delta y\|$ ≥ 1.0	13.9	61.1 ± 25.6	21.3 ± 9.7 (Bkg. Subtracted)	43.3 ± 10.9

- CDF/D0 disagreement?

D. Mietlicki, Moriond, 2012

$t\bar{t}$ p_T & $m_{t\bar{t}}$ at LHC

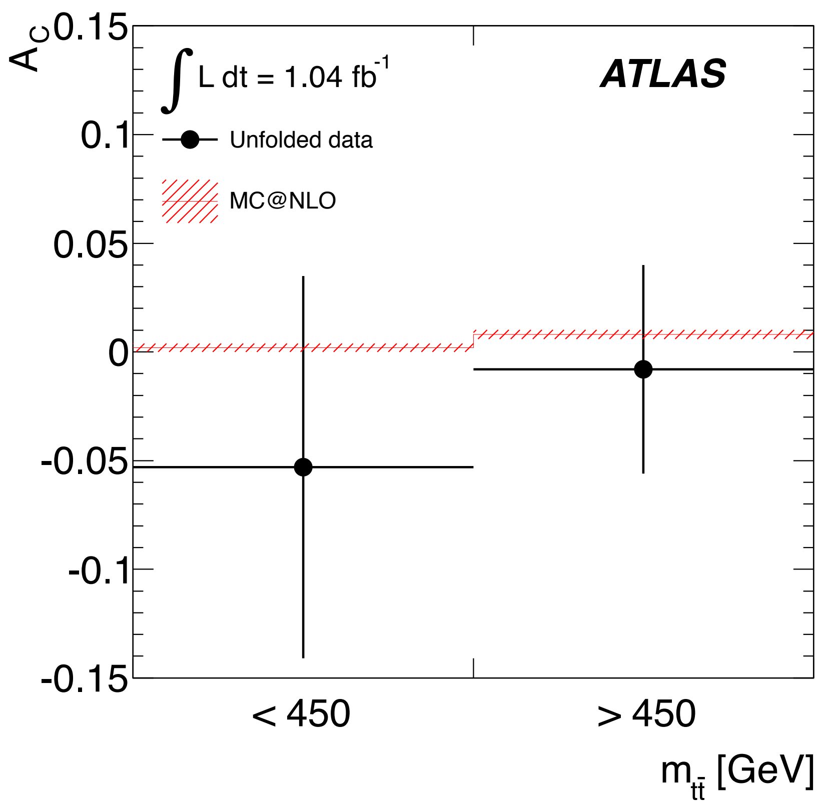
ATLAS, arXiv:1203.5015

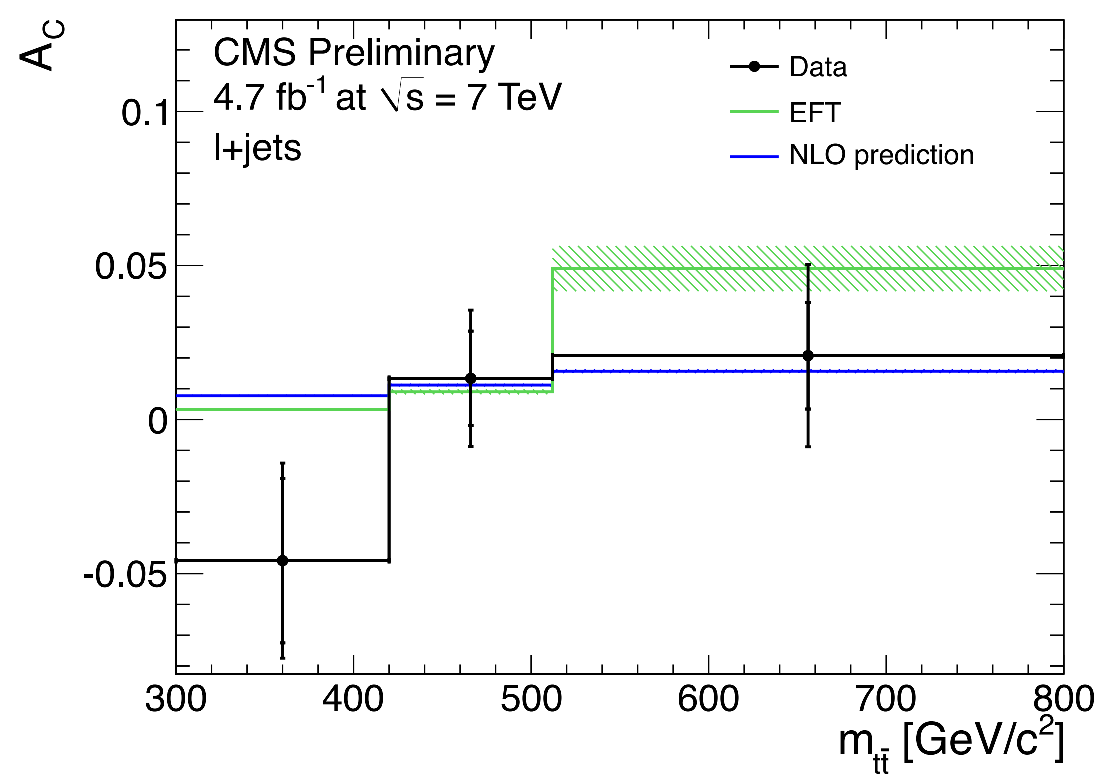


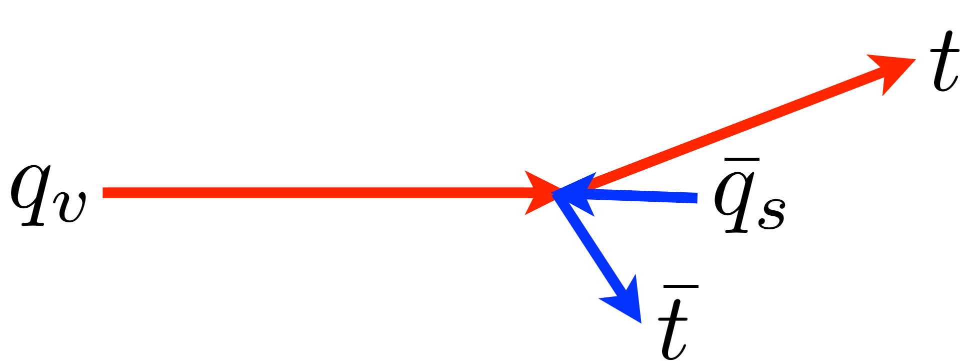
- Good agreement with MC@NLO

$t\bar{t}$ A_C at LHC

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$







- Much smaller than A_{FB}
- Good SM agreement (so far)

Multijet Merging

- Objective: merge LO n-jet matrix elements* with parton showers such that
  - Multijet rates for jet resolution > Q_{cut} (see later) are correct to LO (up to N_{max})
  - Shower generates jet structure below Q_{cut}
  - Leading (and next) Q_{cut} dependence cancels

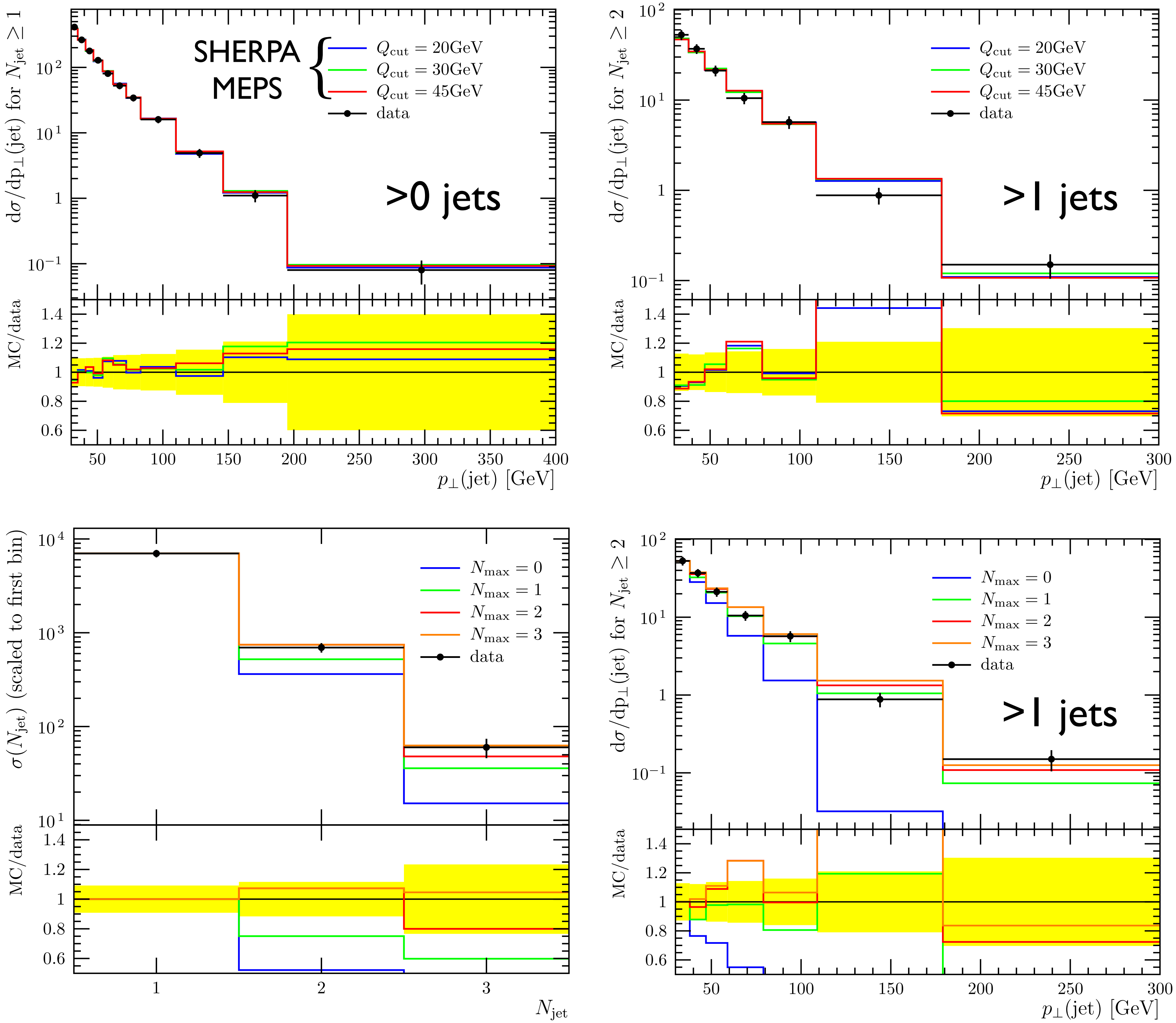
* ALPGEN or MadGraph, $n \lesssim N_{max}$

CKKW: Catani et al., JHEP 11(2001)063

-L: Lonnblad, JHEP 05(2002)063

MLM: Mangano et al., NP B632(2002)343

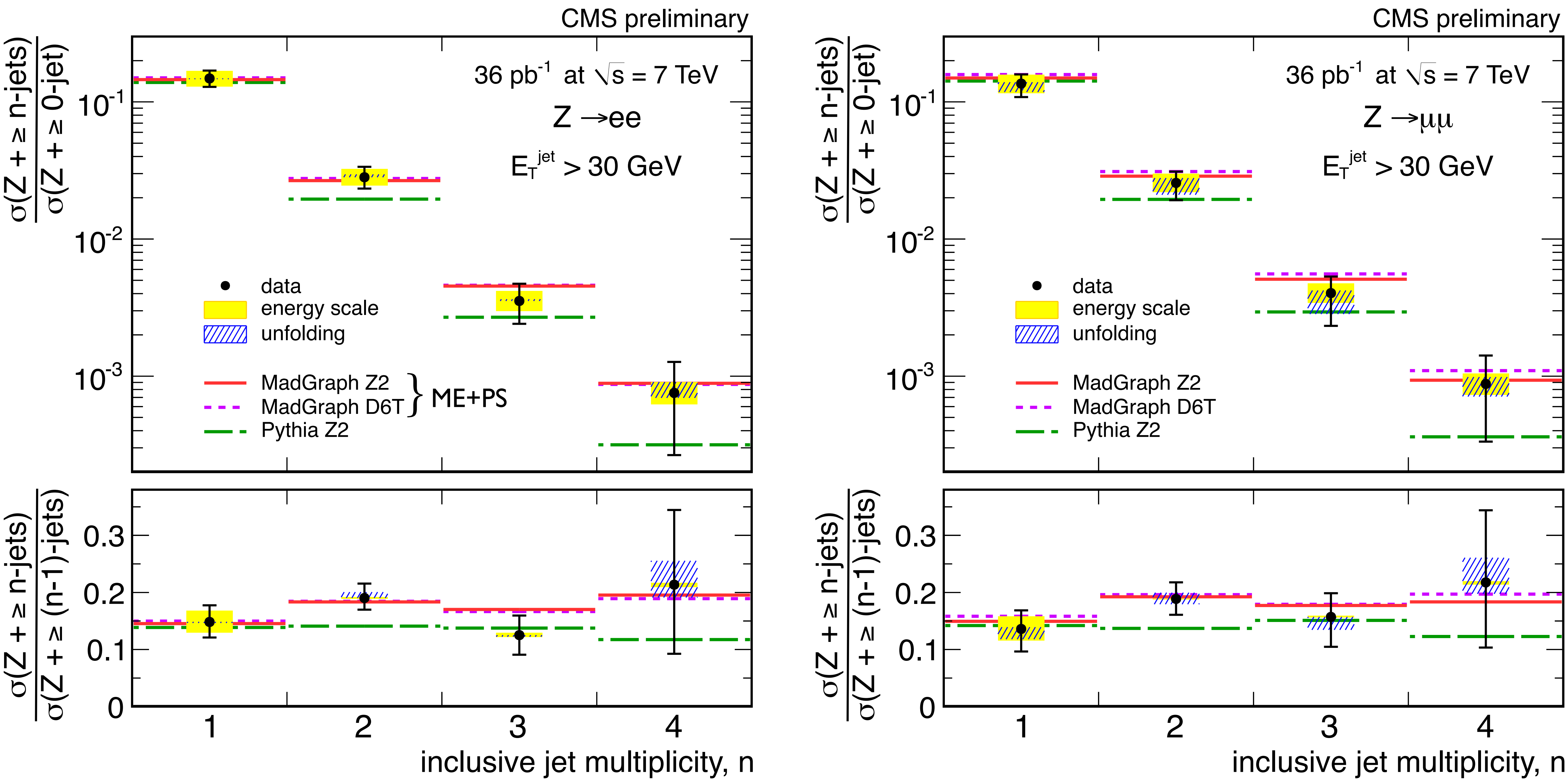
Z^0+jets at Tevatron



- "MEPS"=CKKW
- CDF run II data
- Jet p_T and N_{jets}
- Insensitive to Q_{cut}
- Insensitive to N_{max}>1

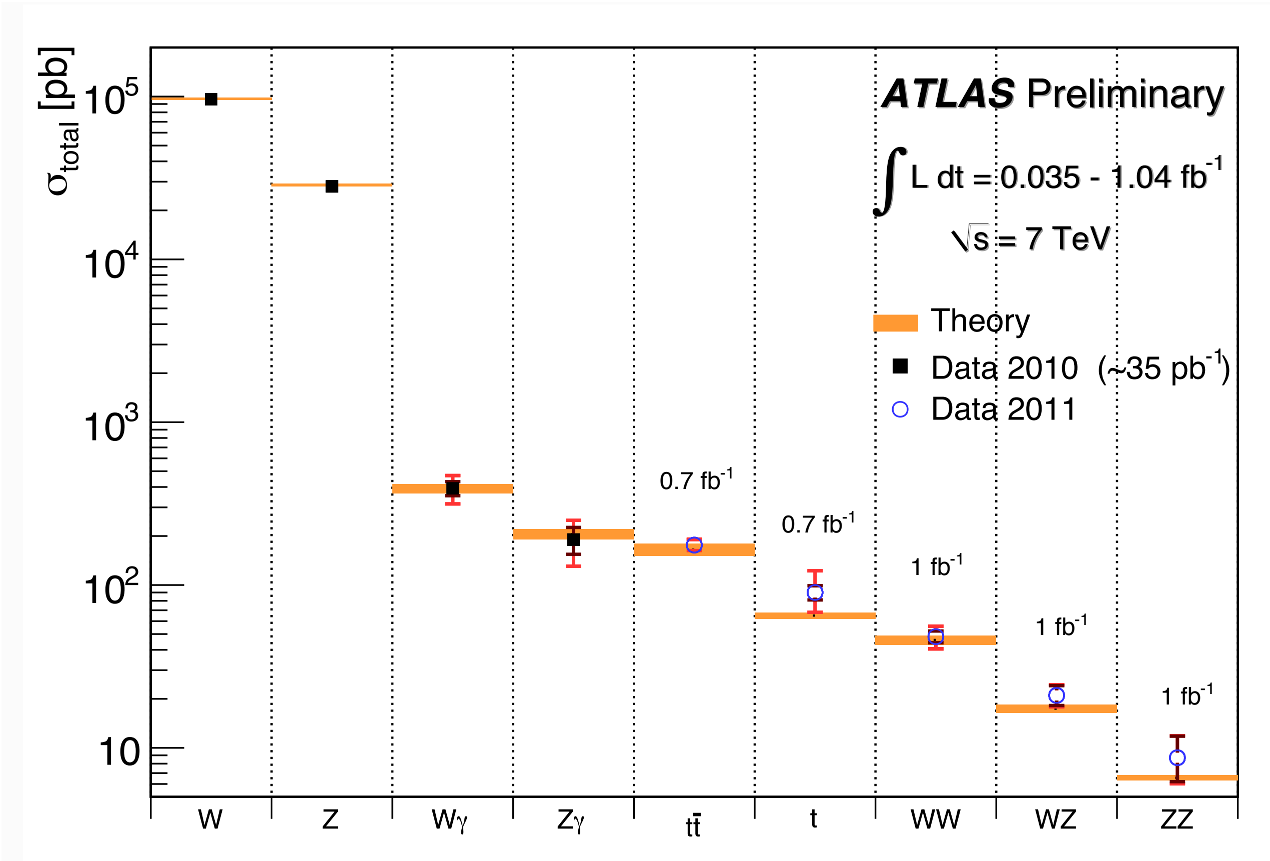
Hoeche, Krauss, Schumann, Siegert, JHEP05(2009)053

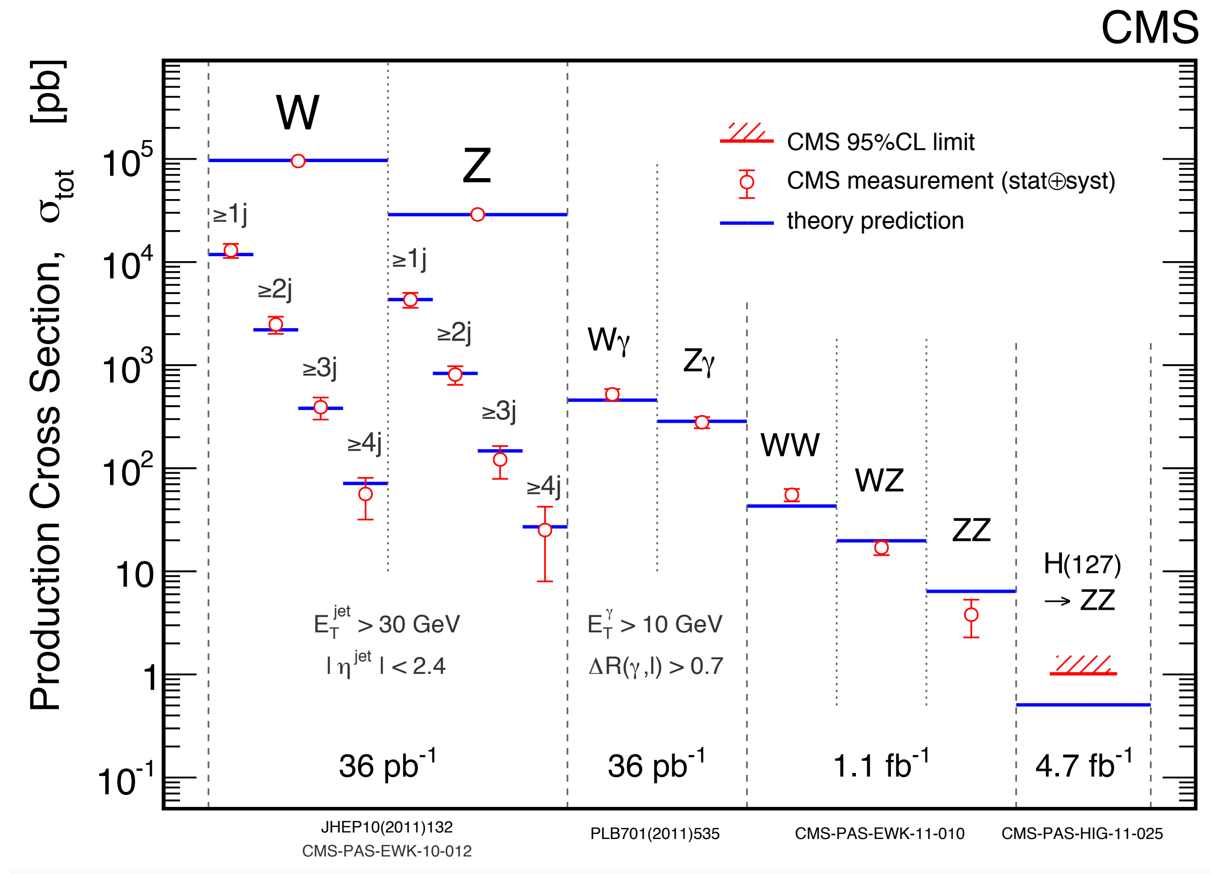
Z⁰+jets at LHC



- Inclusive jet rates (anti-k_t-algorithm -- see later)
- "Very good agreement with predictions from ME+PS simulation, while PS alone starts to fail for njet ≥ 2" V Ciulli, Moriond, 2011

LHC Cross Section Summary

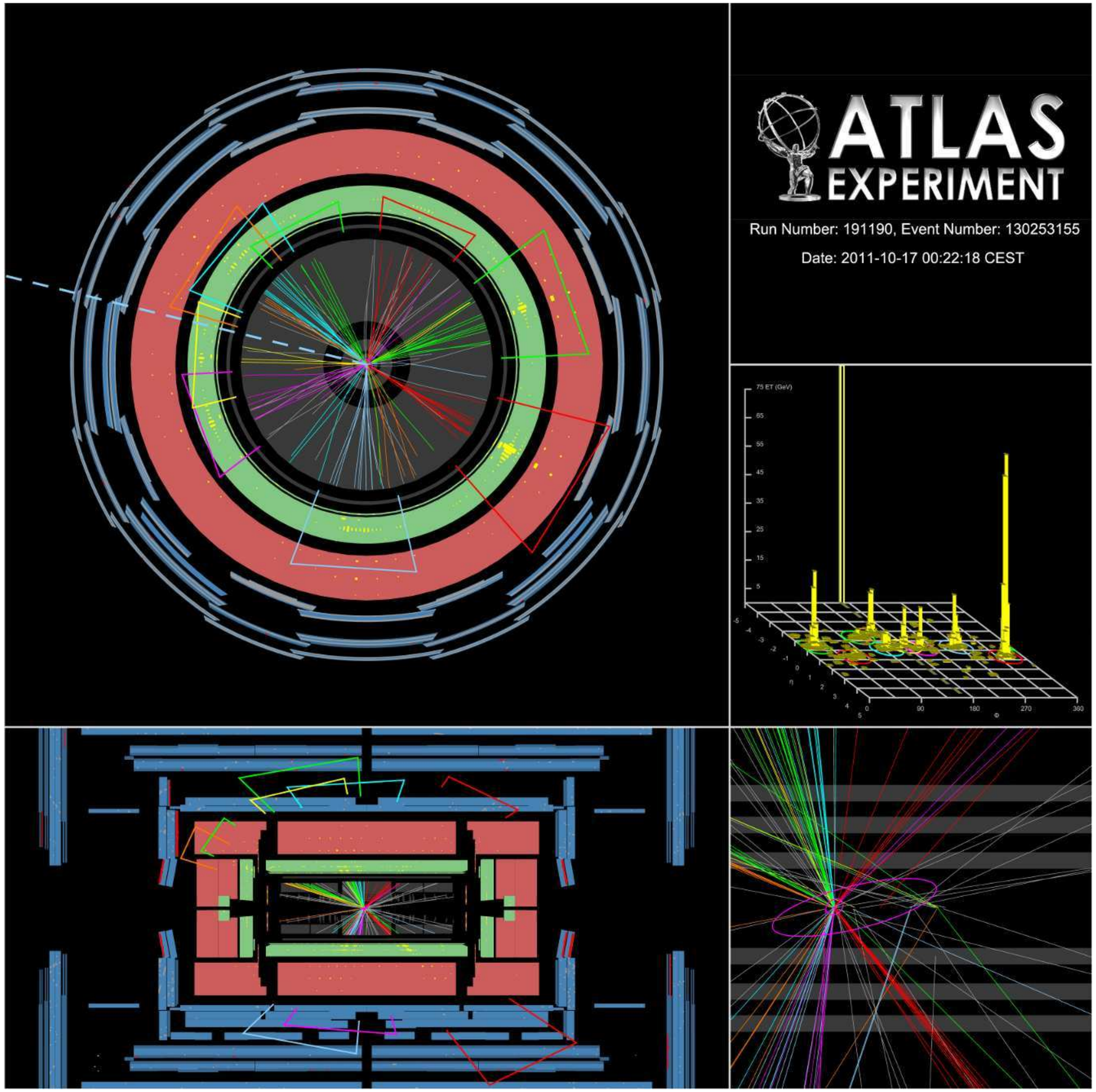




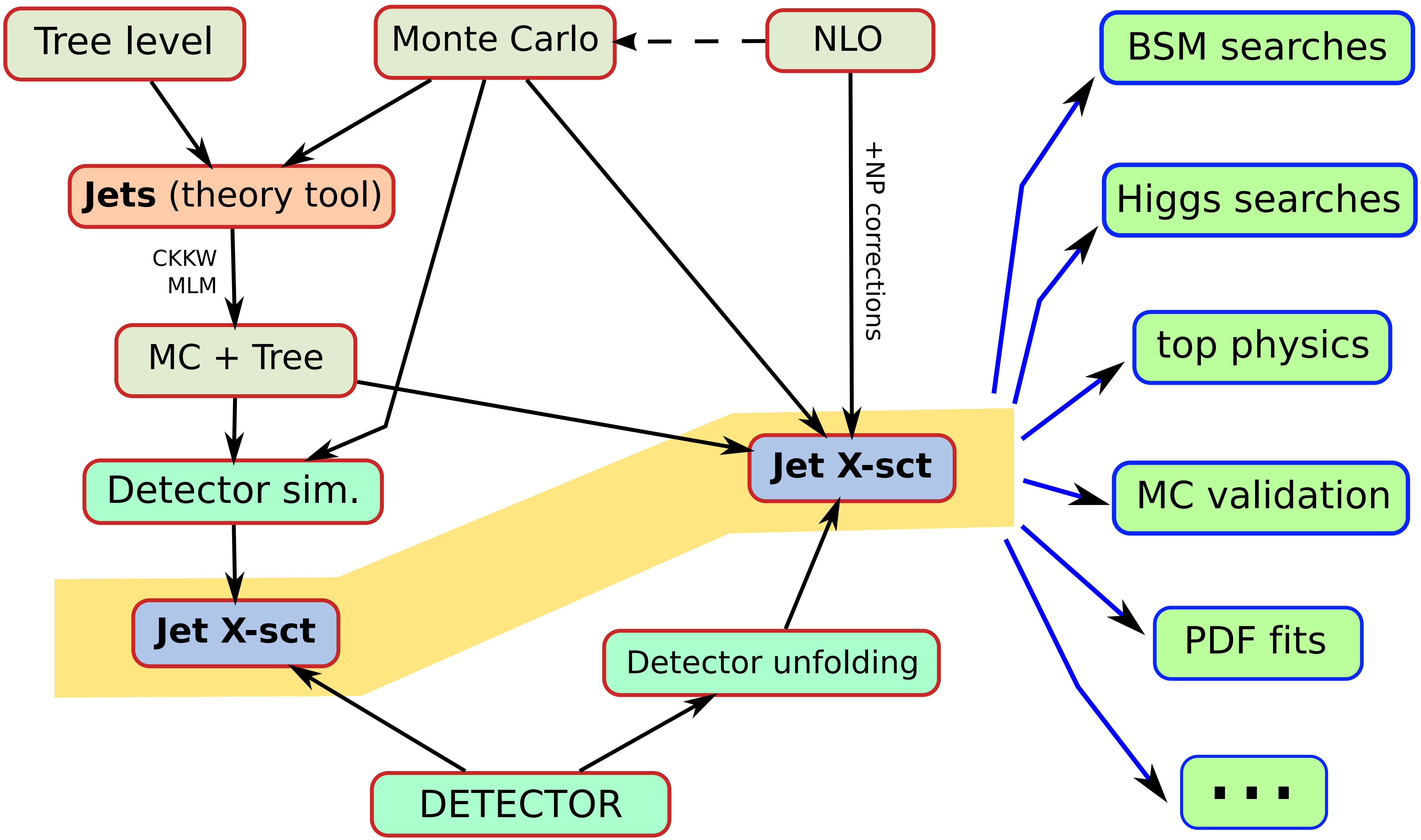
- Surprisingly good agreement
- No sign of non-Standard-Model phenomena (yet) at LHC

Jet Finding Algorithms

A 7-jet event


ATLAS
EXPERIMENT
Run Number: 191190, Event Number: 130253155
Date: 2011-10-17 00:22:18 CEST

Importance of Jets



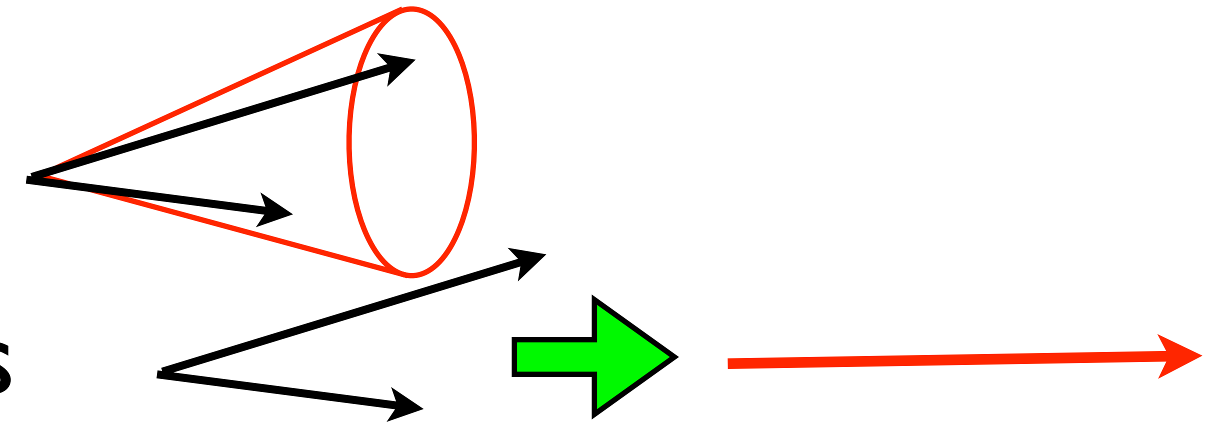
G Salam, 2011

Jet cross sections should be:

- Computable from data in reasonable time
- Calculable in perturbative QCD
- Robust against non-perturbative effects
- Correctable for underlying event

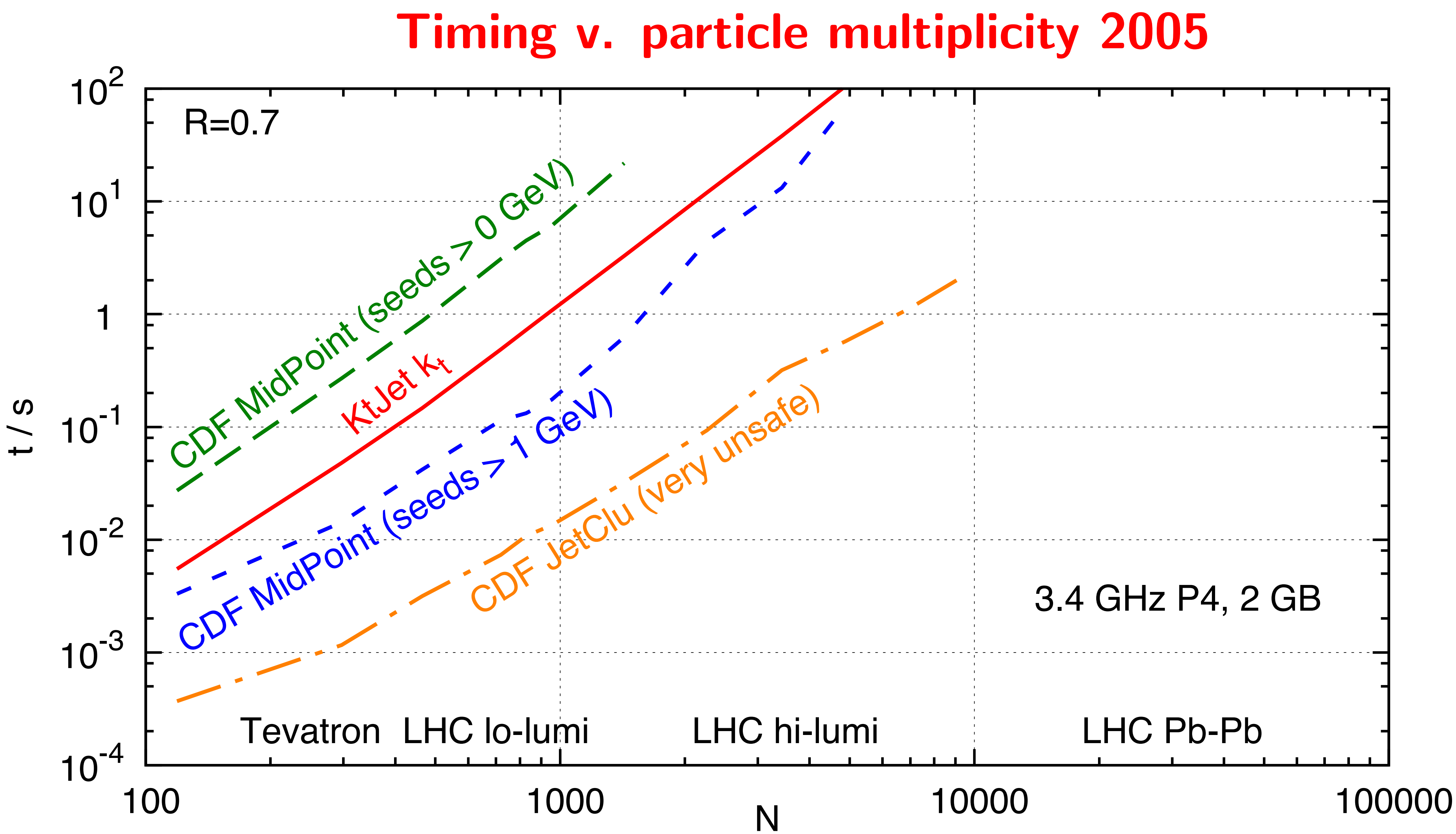
Jet Algorithms

- “Cone” algorithms
- Clustering algorithms



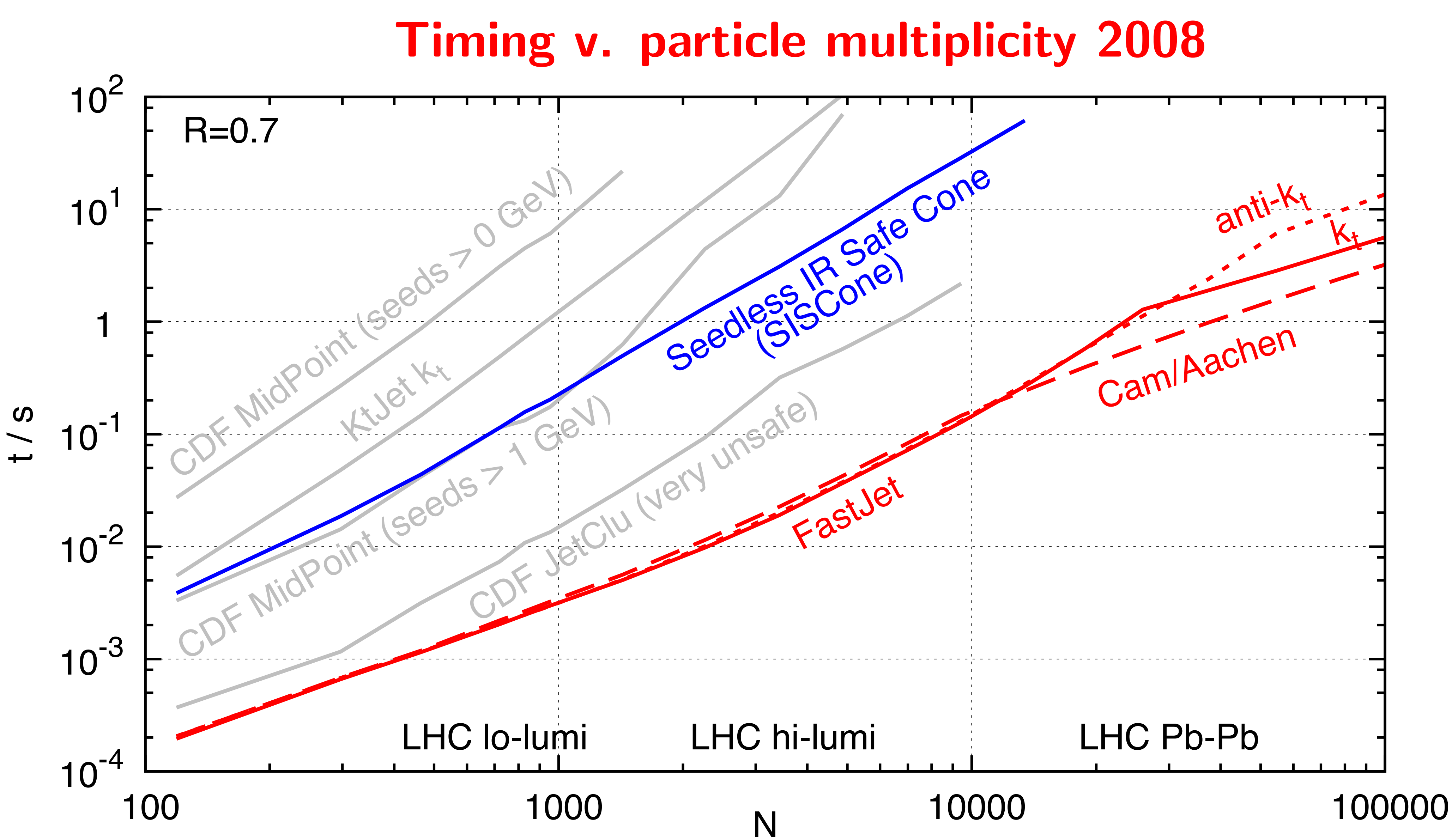
  - LUCLUS (Sjöstrand, 1983)
  - JADE (Bethke et al., 1986)
  - k_T/Durham (Dokshitzer, 1990)
  - Cambridge/Aachen (Dokshitzer et al., 1997)
  - Anti-k_T (Salam et al., 2008)

Jet algorithms: computation



- Computation time $\propto N^3$

Jet algorithms: computation



- Computational geometry ➡ $N^3 \rightarrow N \log N$

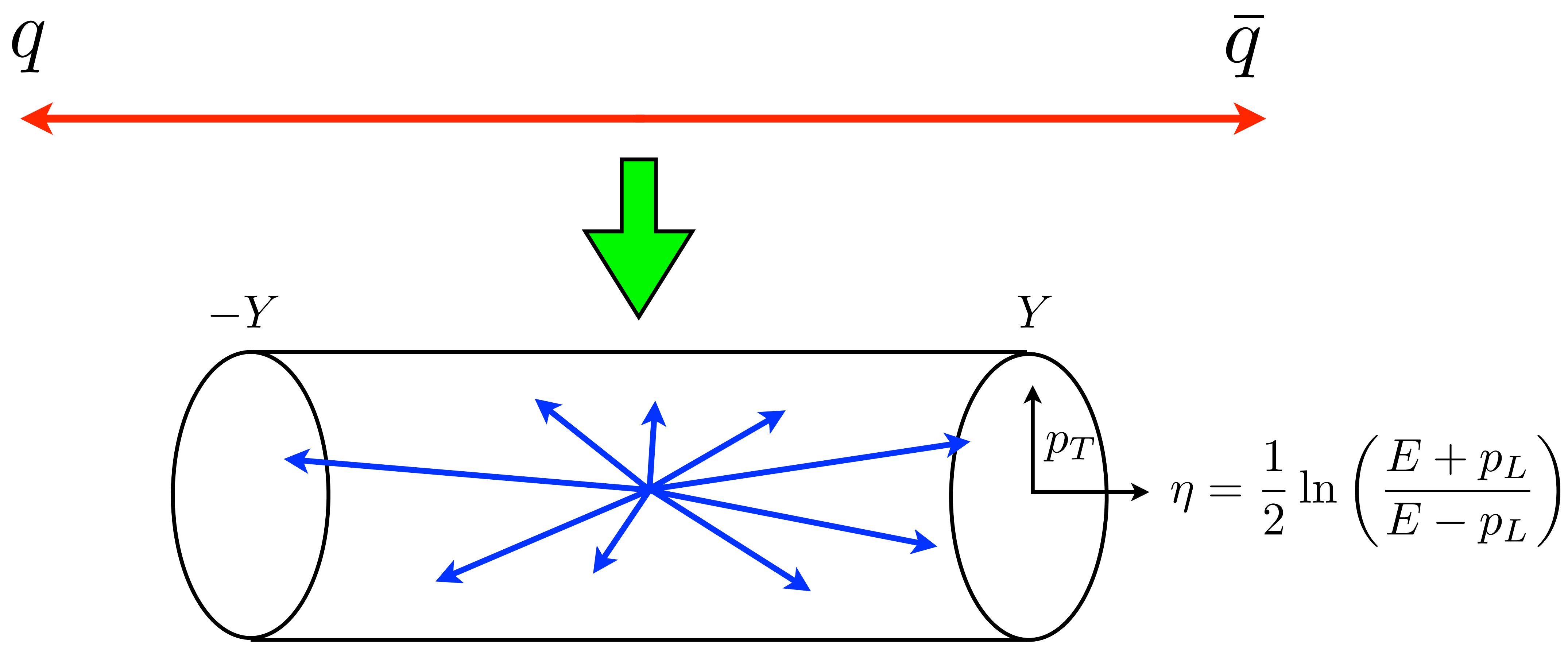
FastJet: Cacciari & Salam, Phys Lett B 641(2006)57

Clustering algorithms

- Algorithms have two key elements:
  - ordering variable v_{ij} : combine smallest if
  - resolution variable $y_{ij} > y$
- LUCLUS: $v_{ij} \sim \{E_i E_j/(E_i + E_j)\}^2\, \theta_{ij}^2\,, \;\; y_{ij} = v_{ij}/E_{\rm cm}^2$
- JADE: $v_{ij} = M_{ij}^2 \sim E_i E_j\, \theta_{ij}^2\,, \;\; y_{ij} = v_{ij}/E_{\rm cm}^2$
- k_T/Durham: $v_{ij} \sim \min\{E_i, E_j\}^2\, \theta_{ij}^2\,, \;\; y_{ij} = v_{ij}/E_{\rm cm}^2$
- Cambridge/Aachen: $v_{ij} \sim \theta_{ij}^2\,, \;\; y_{ij} = y_{ij}^{k_T}$
- Anti-k_T: $v_{ij} \sim \theta_{ij}^2/\max\{E_i, E_j\}^2\,, \;\; y_{ij} = y_{ij}^{k_T}$

Hadronization

- Simple "tube" model describes many features

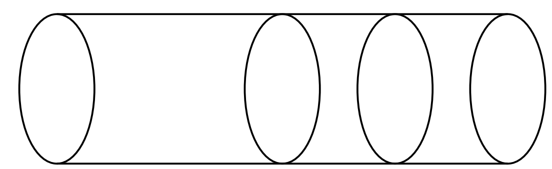


$$Q = E_{\rm cm} = \int d\eta \, d^2 p_T \, \rho(p_T) p_T \cosh \eta = 2\lambda \sinh Y$$

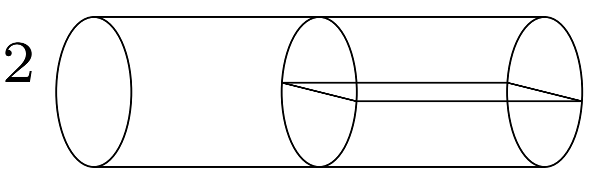
$$\lambda = \int d^2 p_T \, \rho(p_T) p_T = N_{\rm had} \langle p_T \rangle / 2Y$$

Hadronization

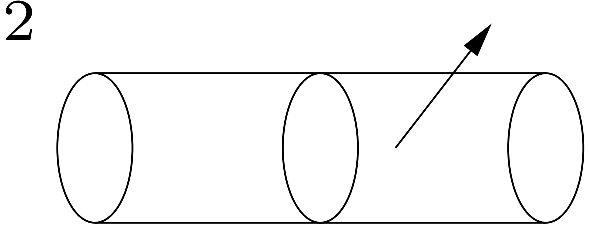
- Algorithm should classify tube as 2-jet
  - $\langle y_{3-\mathrm{jet}} \rangle$ smallest is best
- JADE: $\langle y_{3-\mathrm{jet}} \rangle \sim \lambda/Q$



- LUCLUS, k_T/Durham: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda \ln Q/Q)^2$

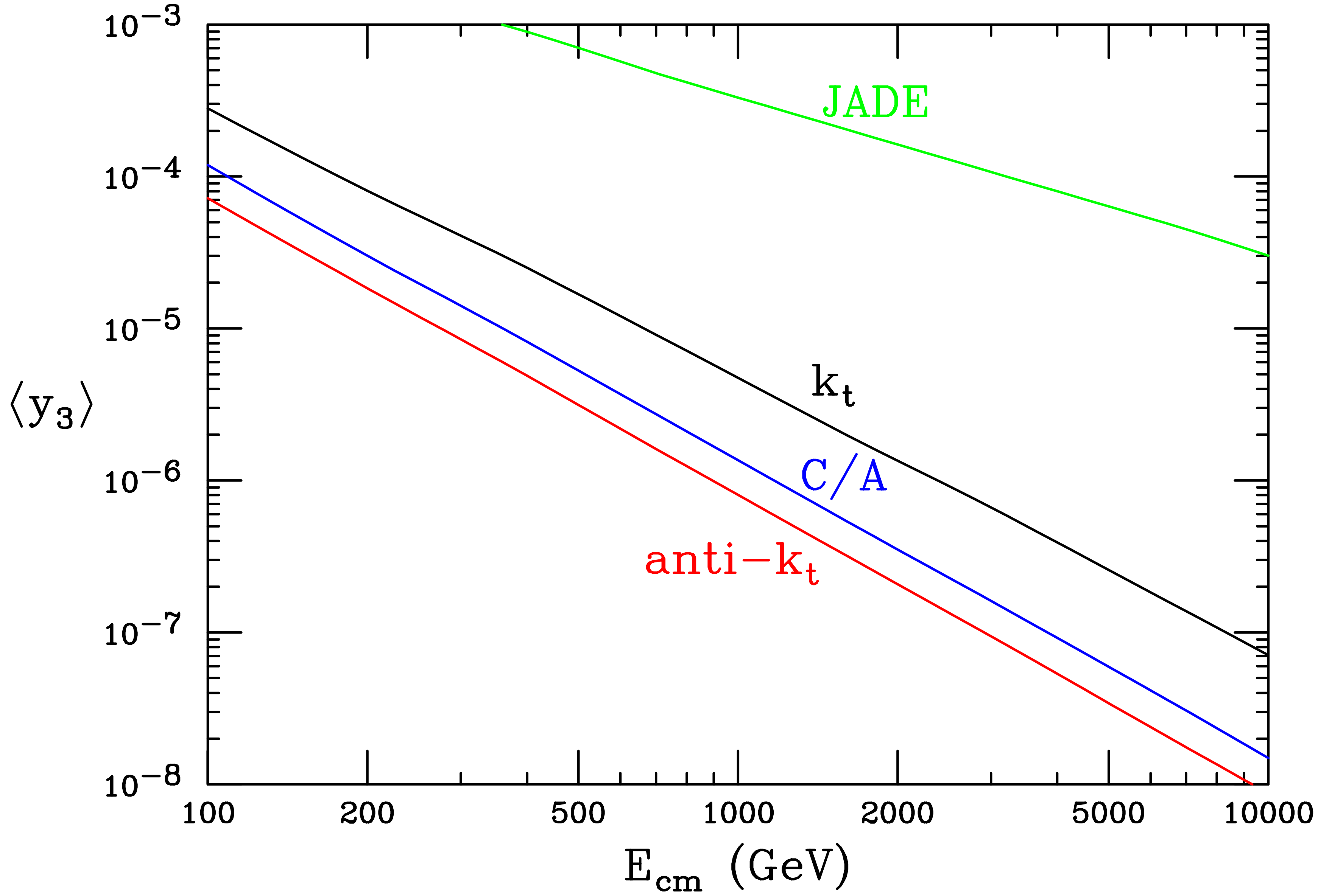


- Cambridge/Aachen: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda \ln \ln Q/Q)^2$



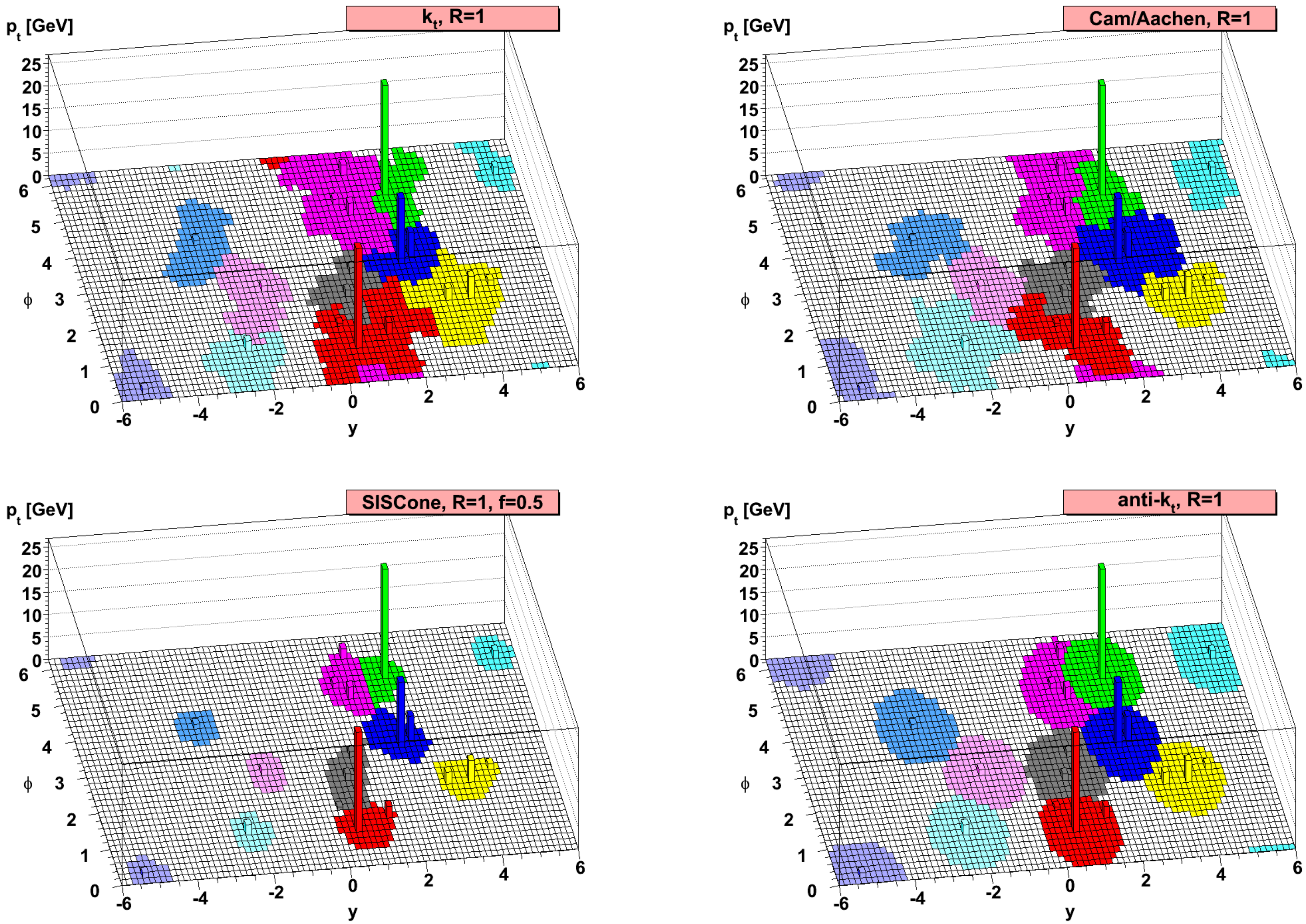
- Anti-k_T: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda/Q)^2$

Jet algorithms: hadronization



- Anti-k_T is best for small hadronization effect

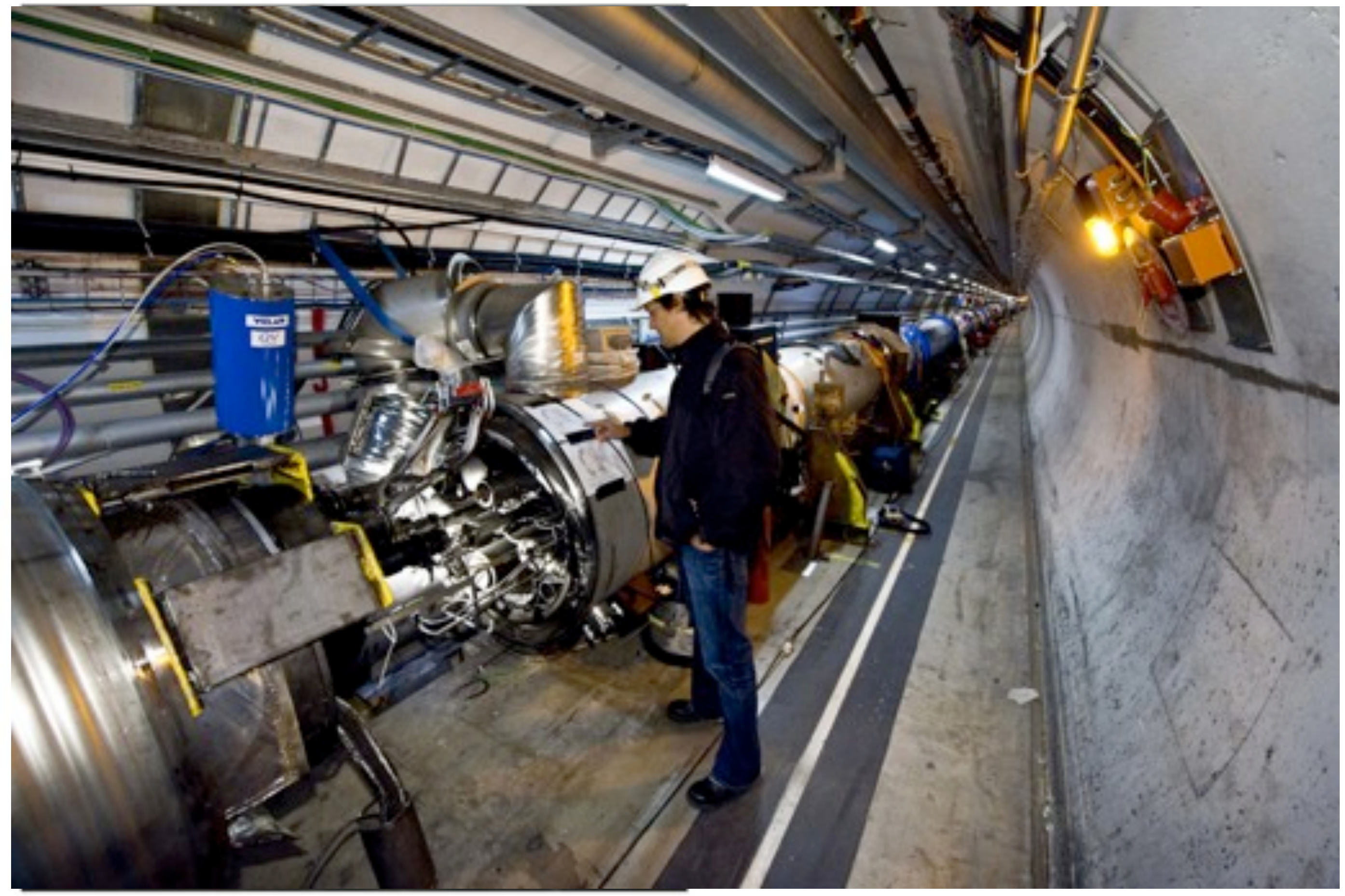
Jet algorithms: underlying event



Cacciari, Salam, Soyez, JHEP04(2006)063

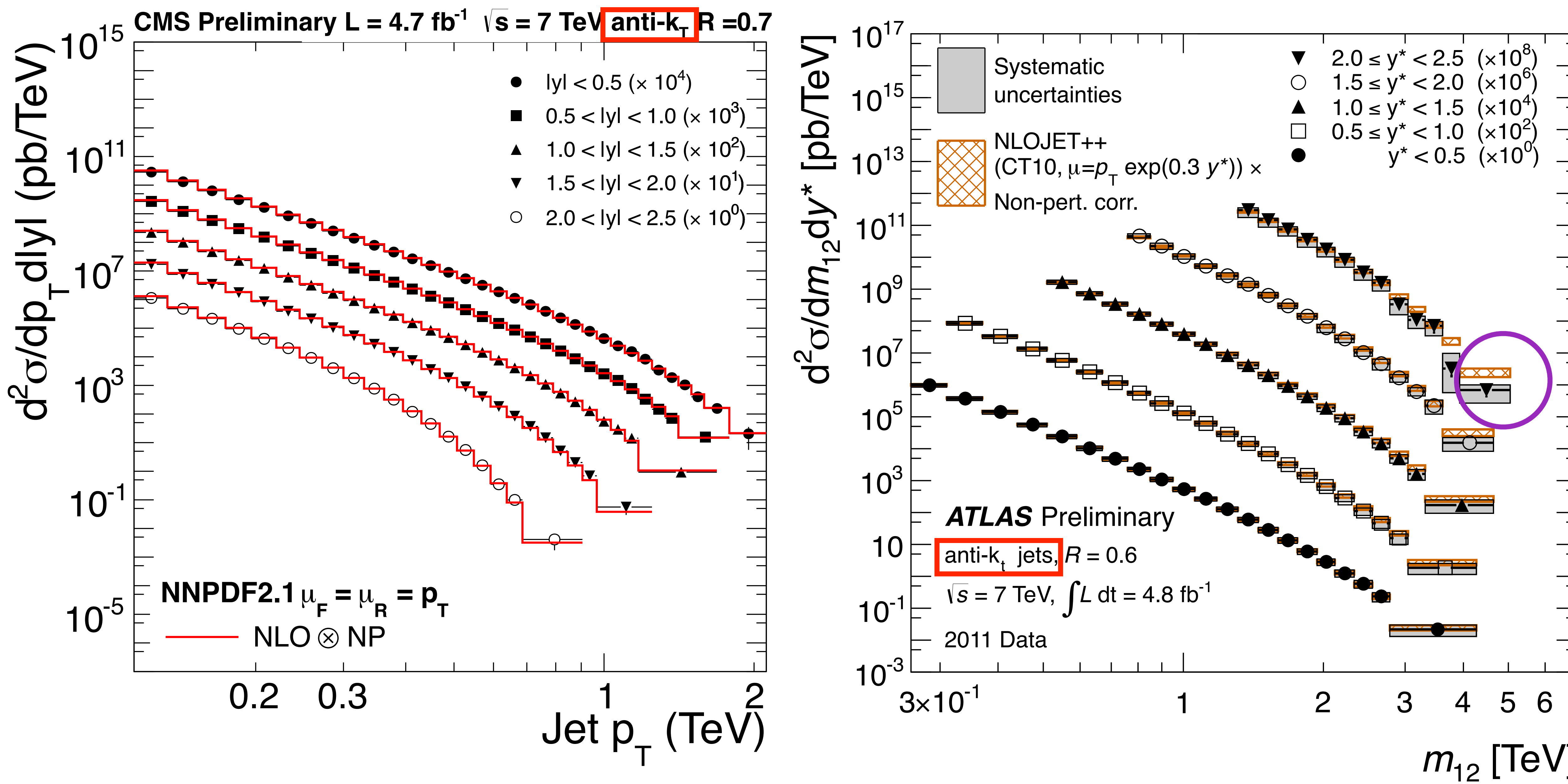
- Anti-k_T is best for controlled UE subtraction

LHC Quench Incident



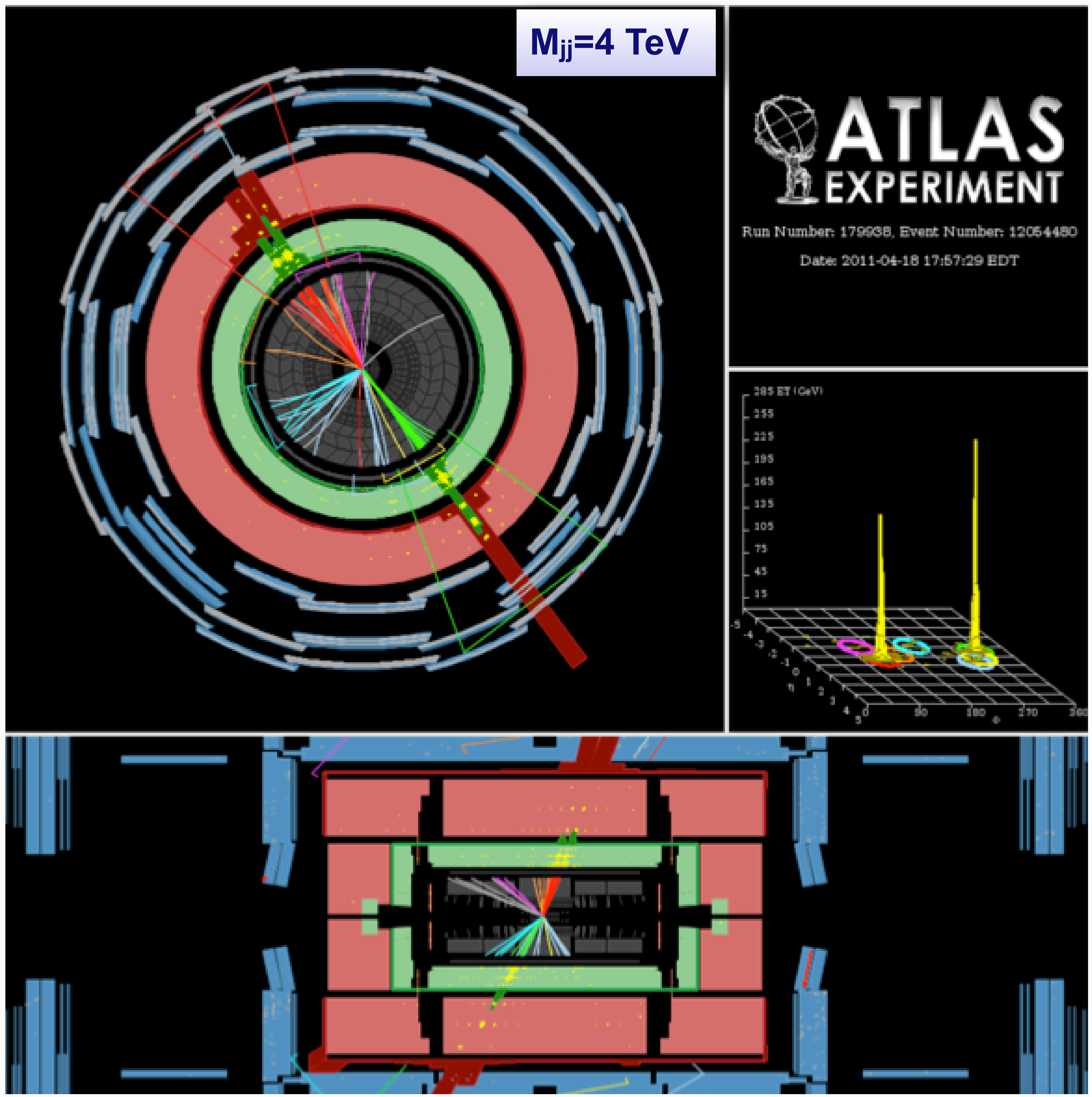
- First beams on 10 Sept 2008
- On 19 Sept 2008, a electrical fault caused ~100 bending magnets to quench
- 6 tons of liquid He lost, 53 magnets damaged
- Startup delayed >1 year ➡ time to switch to anti-k_T !

Jet cross sections at LHC

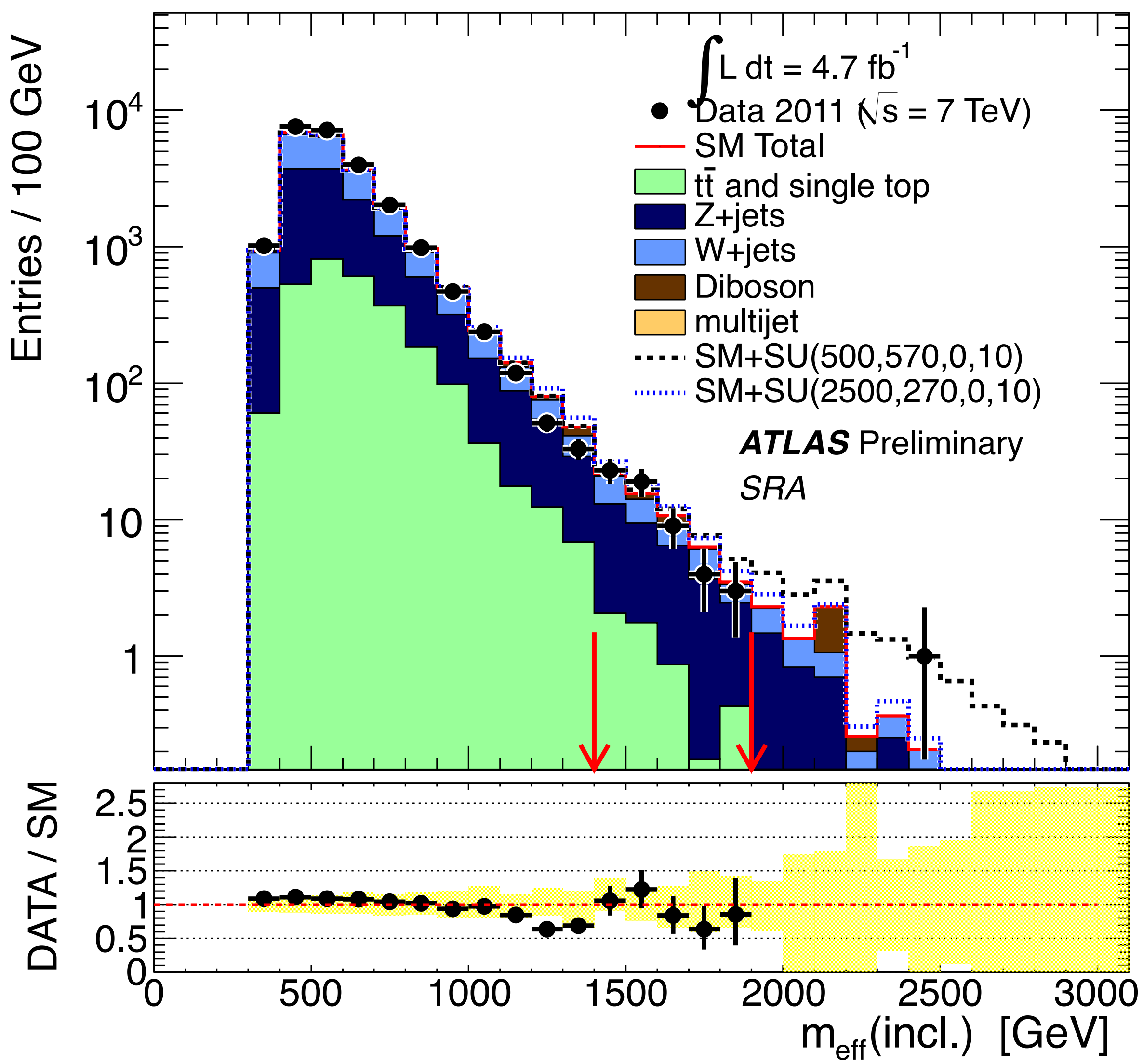


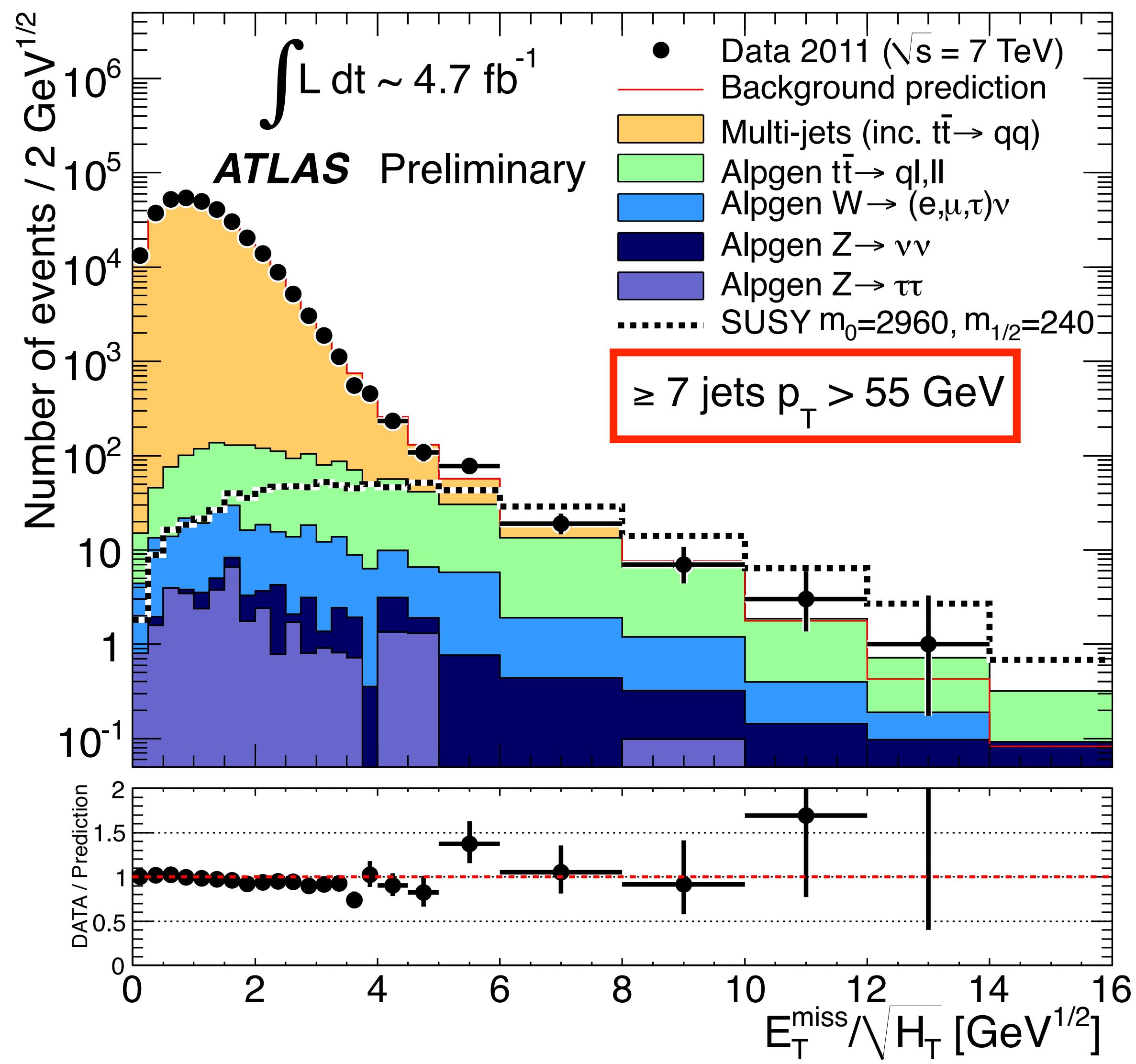
- NLO with hadronization corrections (NP)
- m_{12} = dijet invariant mass

A high-mass dijet



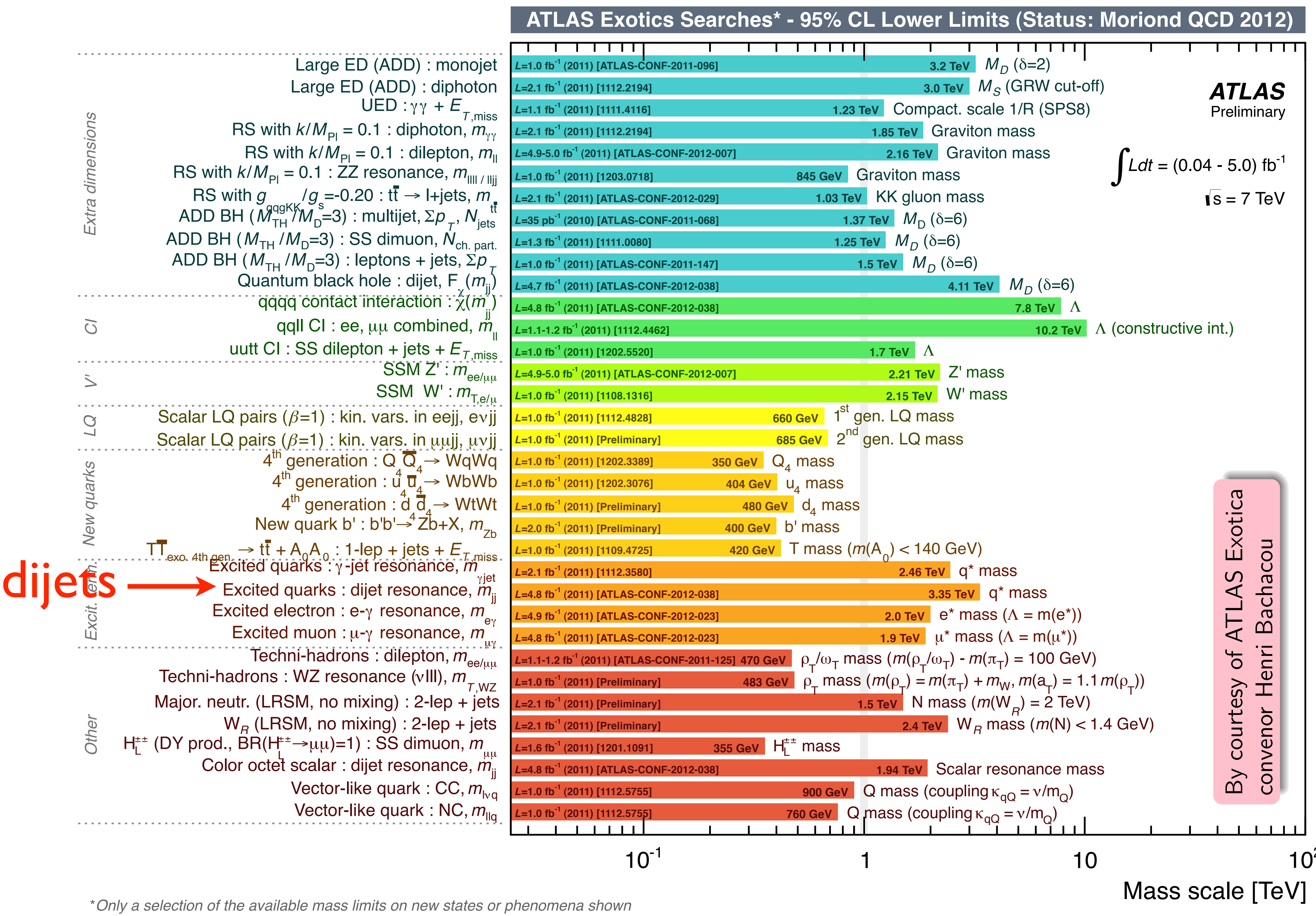
Searching for new signals



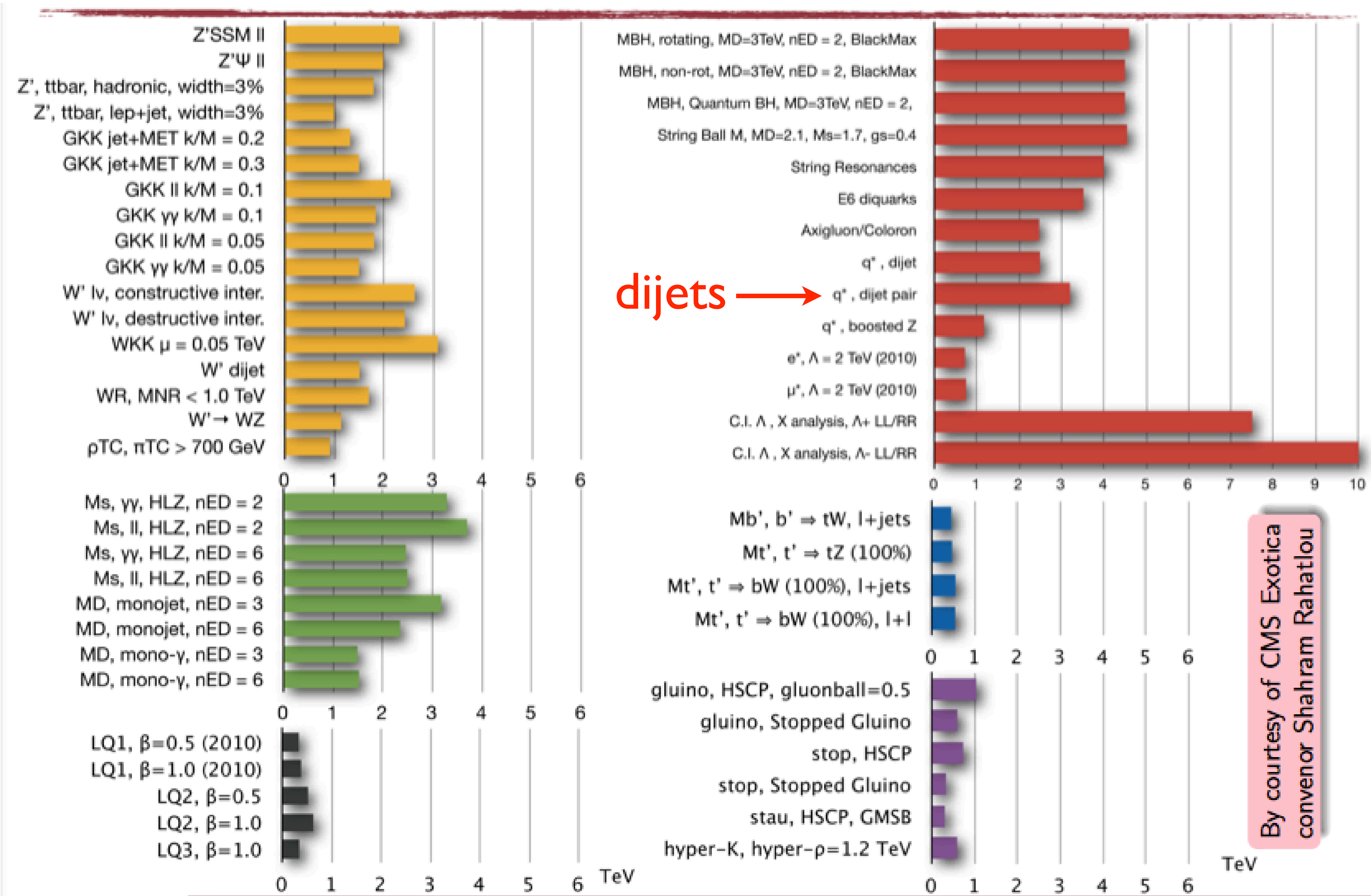


- "SUSY" = Constrained Minimal Supersymmetric Standard Model
- Huge parameter space still to explore

ATLAS Search Summary



CMS Search Summary



Conclusions & Prospects

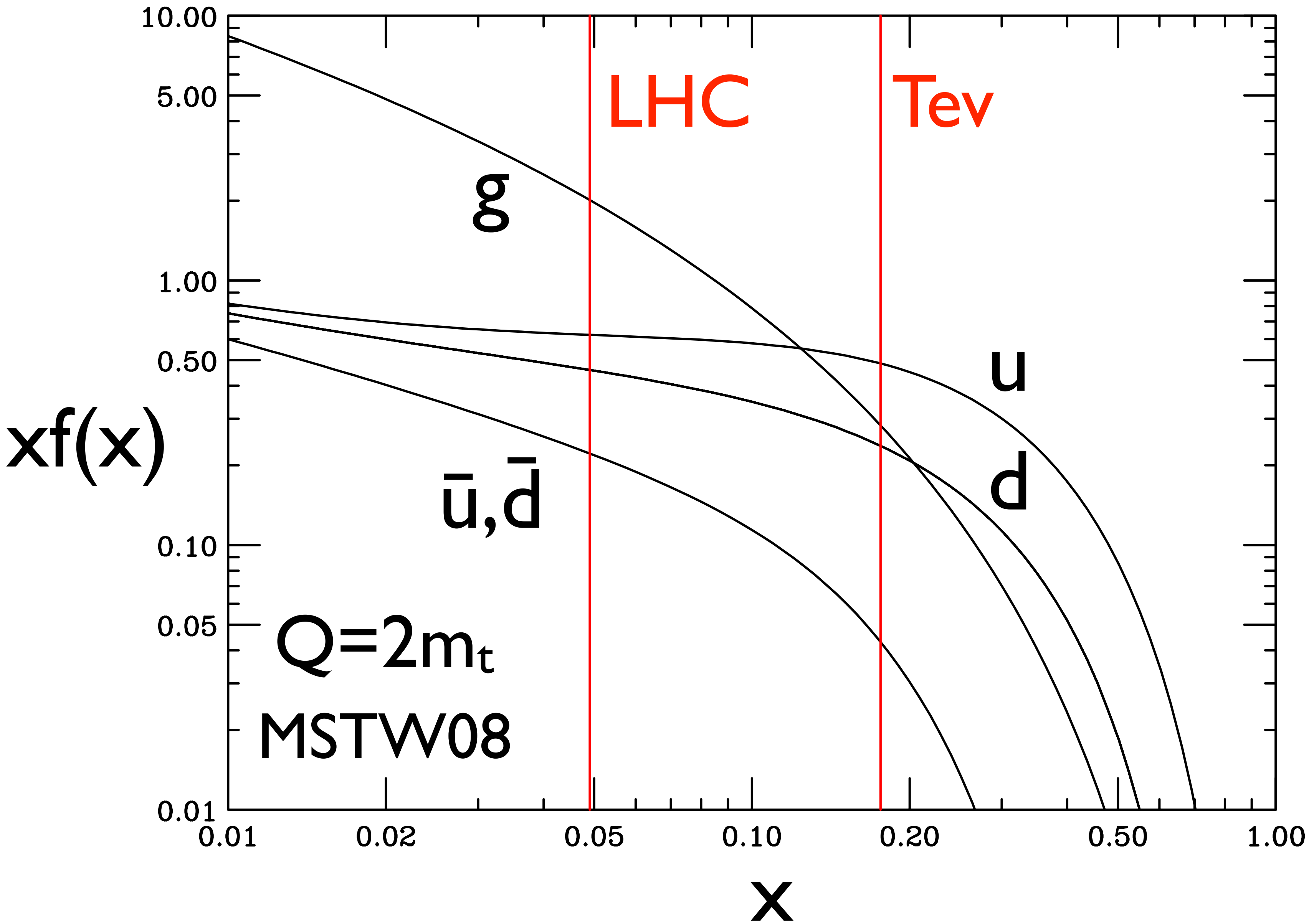
- Event generators now have more controlled precision
  - Surprisingly good agreement with first LHC data
  - No sign of non-Standard-Model processes (yet)
  - Conflicting top quark results from Tevatron
  - Next step: multijet NLO merging (MENLOPS)
- LHC delay meant better jet algorithms (anti-k_t) adopted
  - Multijet (up to 7) and dijet (up to 4 TeV) cross sections explored for signs of non-SM processes
  - Next step: use of jet substructure for searches

And finally...


- Thanks to my Lund colleagues/competitors!

Backup

Parton distributions



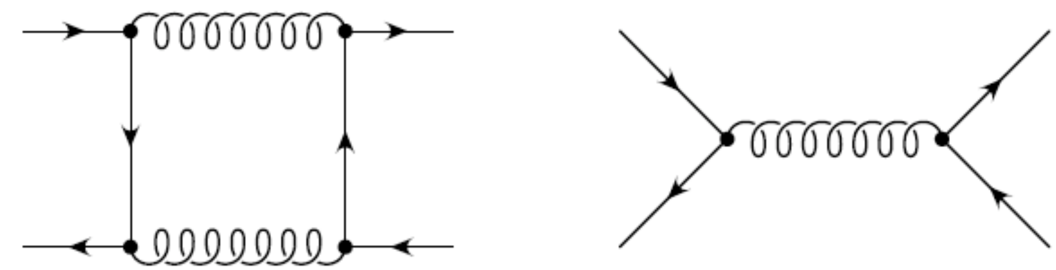
- $u\bar{u} \to t\bar{t}$ dominates at Tevatron, $gg \to t\bar{t}$ at LHC

Top quark asymmetry A_{FB}

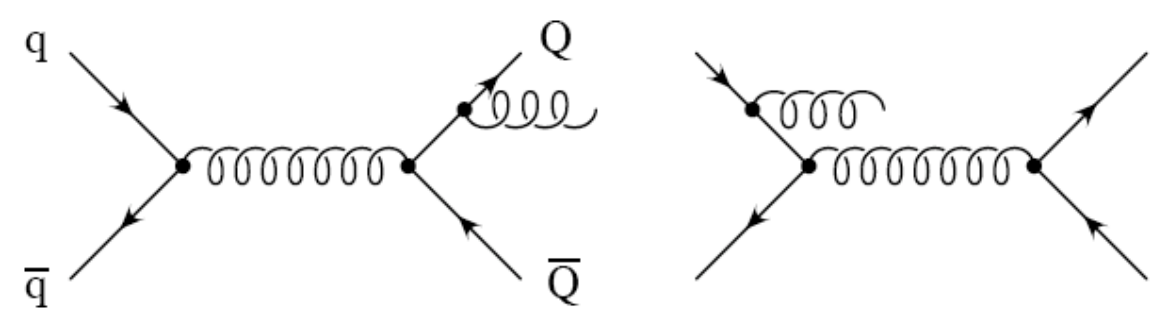
- Only $q\bar{q}$ asymmetric
- NLO effect ~5% at parton level
- t prefers q direction

$$y \equiv \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$$

➡ Expect $y_t > y_{\bar{t}}$



$A^{t\bar{t}} > 0$ dominant (low $p_T^{t\bar{t}}$)

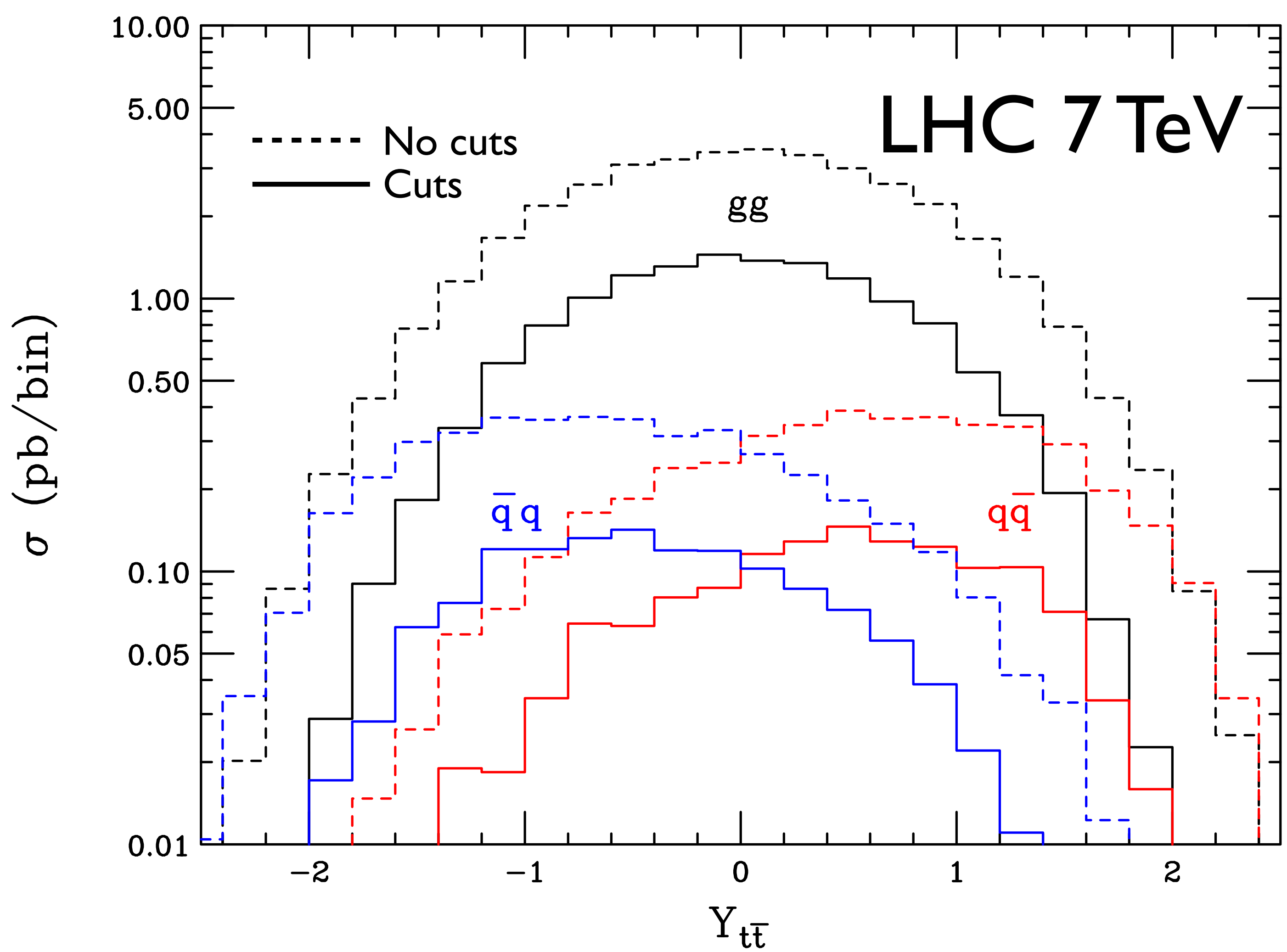


$A^{t\bar{t}} < 0$ if extra jet or high $p_T^{t\bar{t}}$

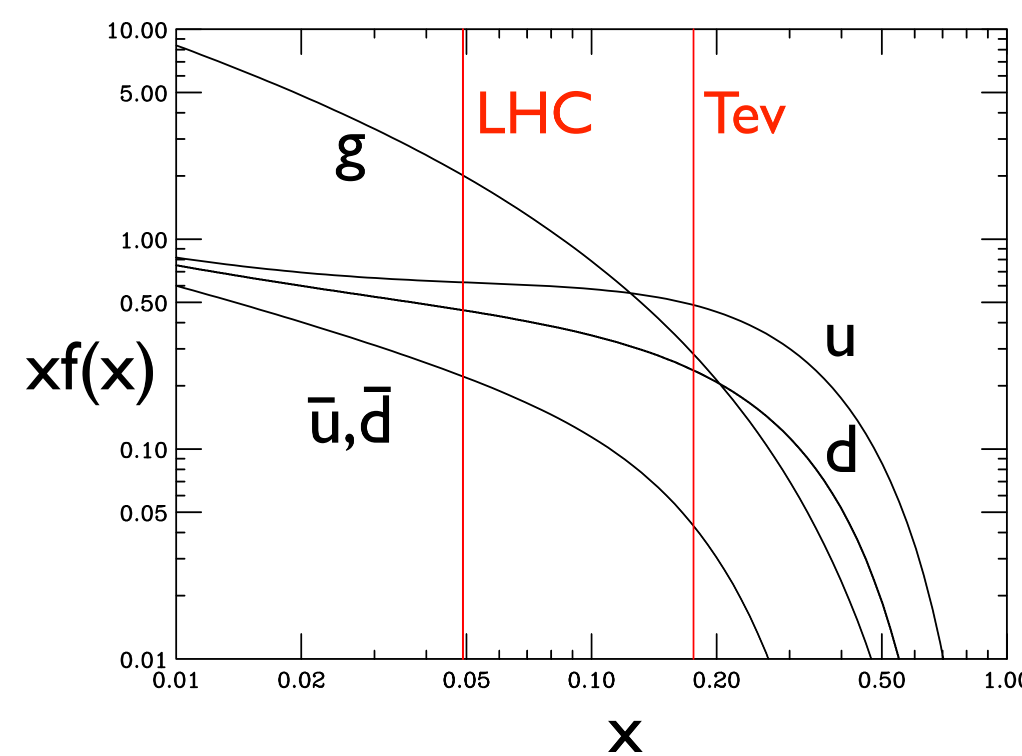
$$\Delta y = y_t - y_{\bar{t}} \quad \Rightarrow \quad A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} > 0$$

Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect is small (plots show MC truth for 2 fb^{-1})

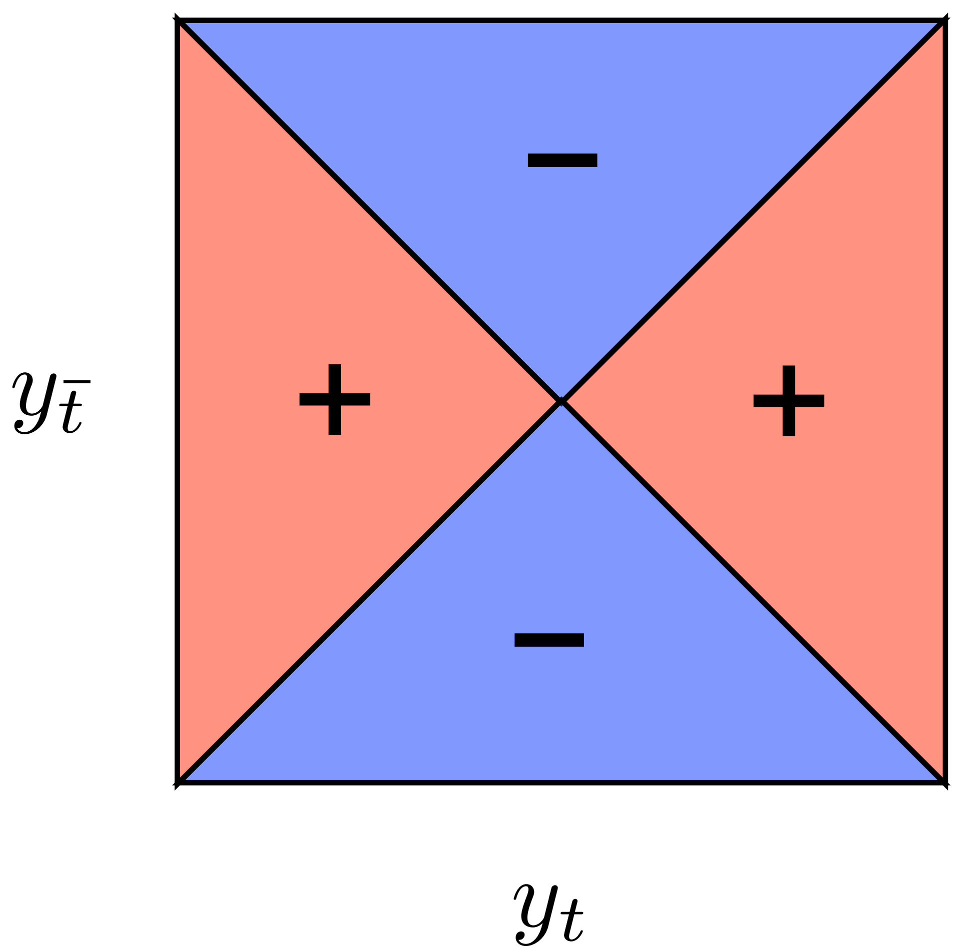


$$\Delta y = y_t - y_{\bar{t}}\ ,\quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$



Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Rapidity correlation should be as shown below
- Top rapidity distribution should be wider



$$\Delta y = y_t - y_{\bar{t}}\ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}| > 0 \quad \Longleftrightarrow \quad \Delta y \cdot Y_{t\bar{t}} > 0$$