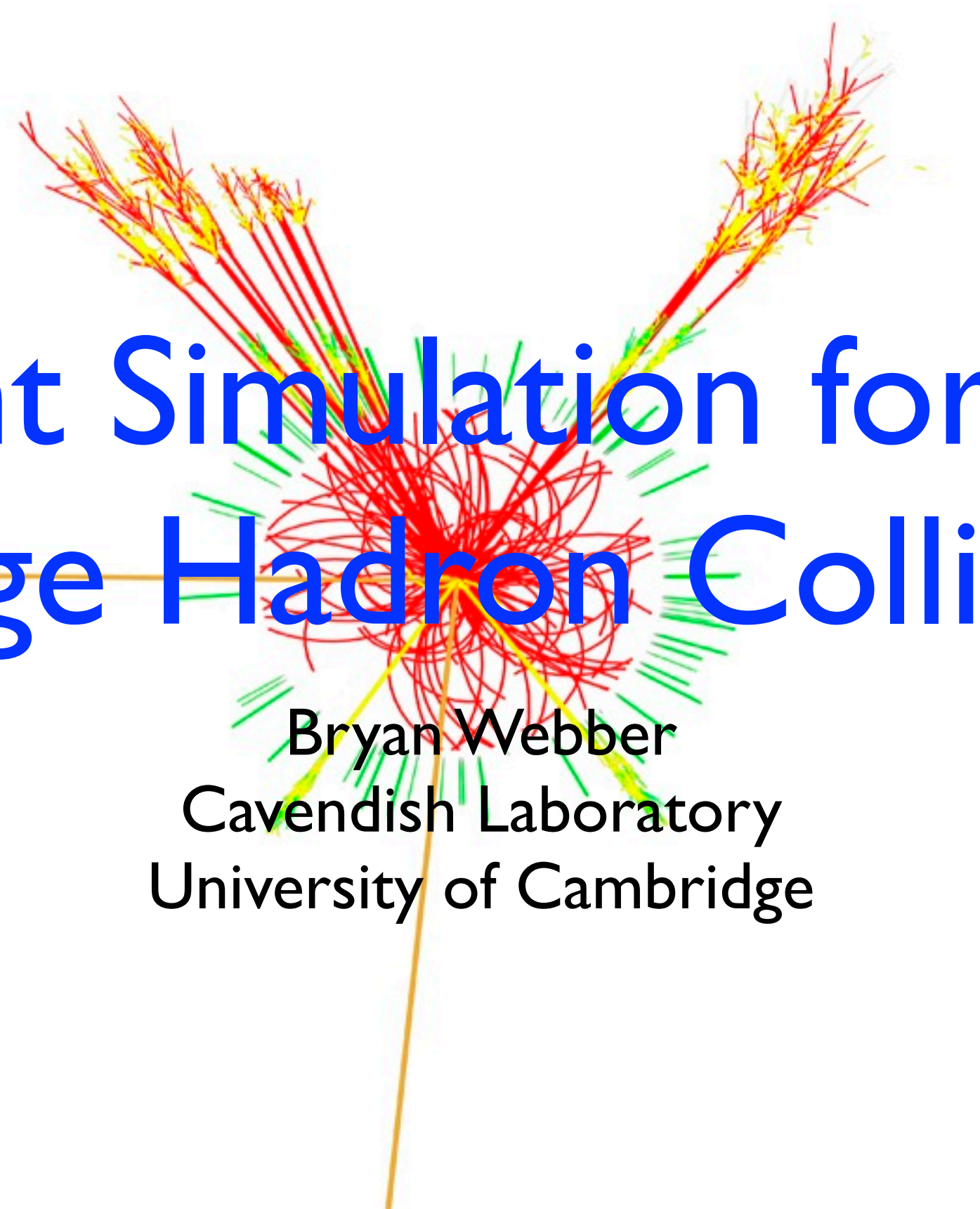


A visualization of a particle collision event simulation. It shows a central point from which numerous lines radiate outwards. The lines are primarily red, with some green and yellow lines interspersed. The lines are thicker near the center and become thinner as they extend outwards, suggesting a branching or showering process. The overall shape is roughly circular, with the lines filling most of the frame.

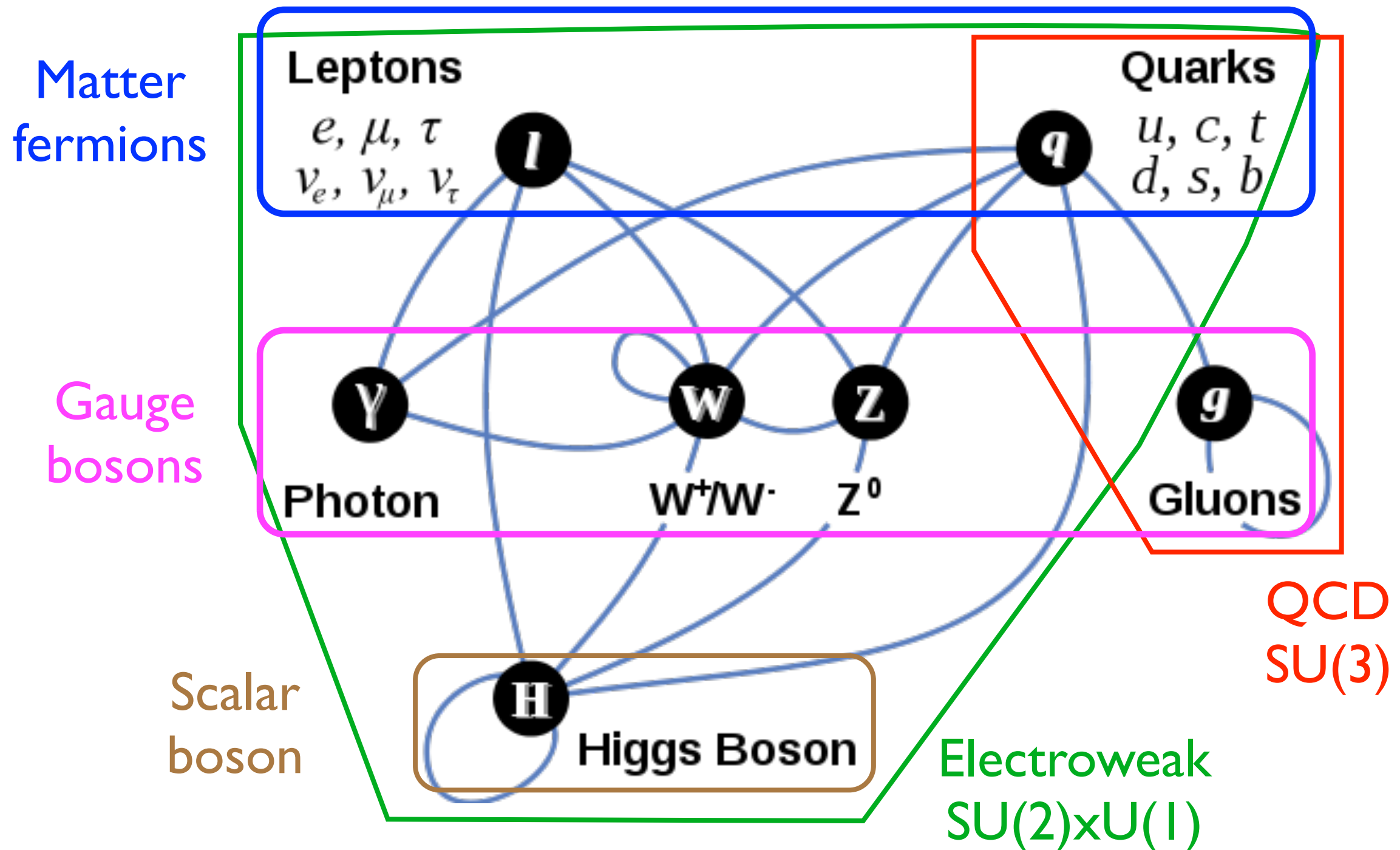
Event Simulation for the Large Hadron Collider

Bryan Webber
Cavendish Laboratory
University of Cambridge

Event Simulation for the Large Hadron Collider

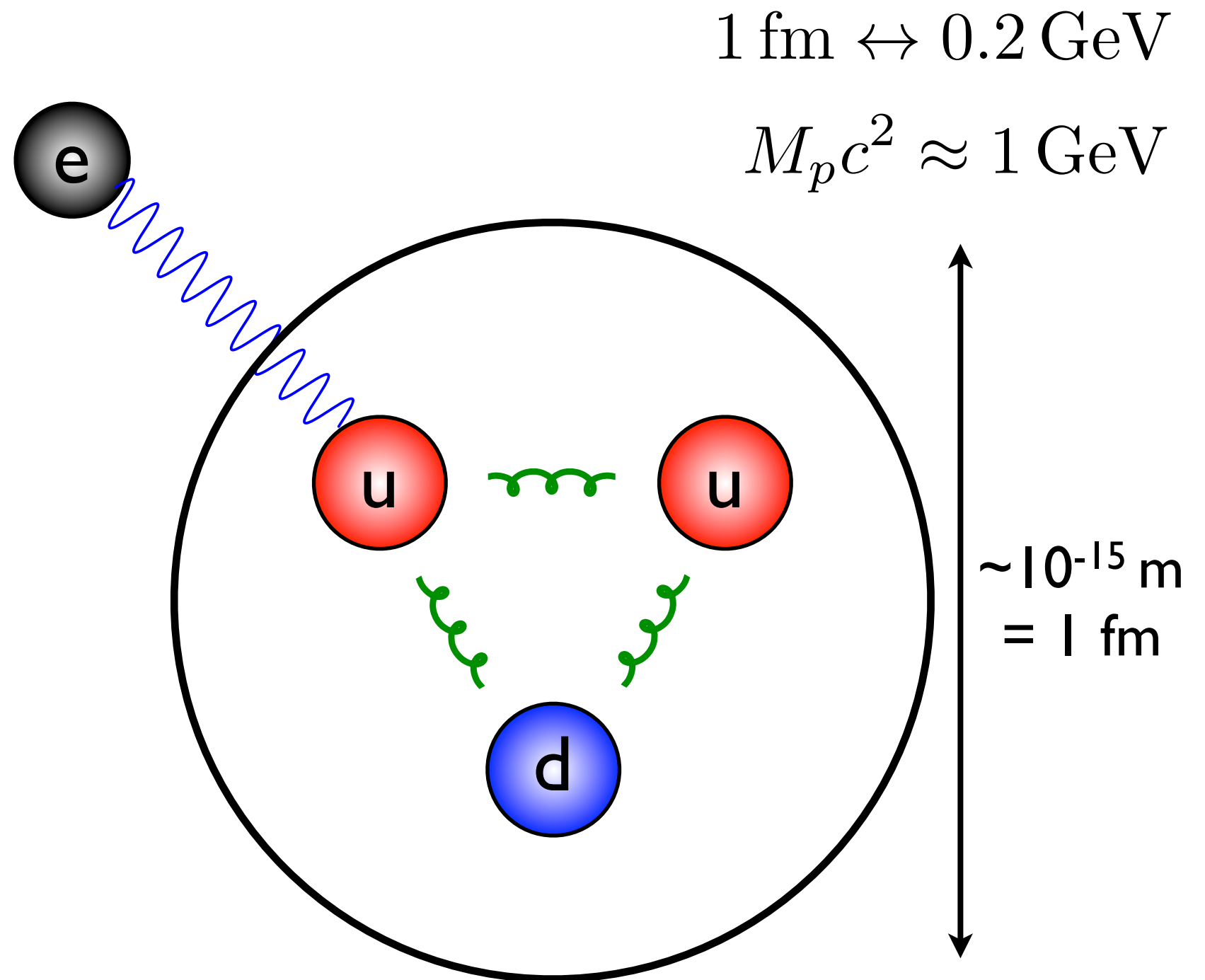
- The Standard Model
- Lepton-hadron and hadron-hadron collisions
- Event generation, matching and merging
- The Higgs boson
- Beyond the Standard Model
- Conclusions and prospects

The Standard Model

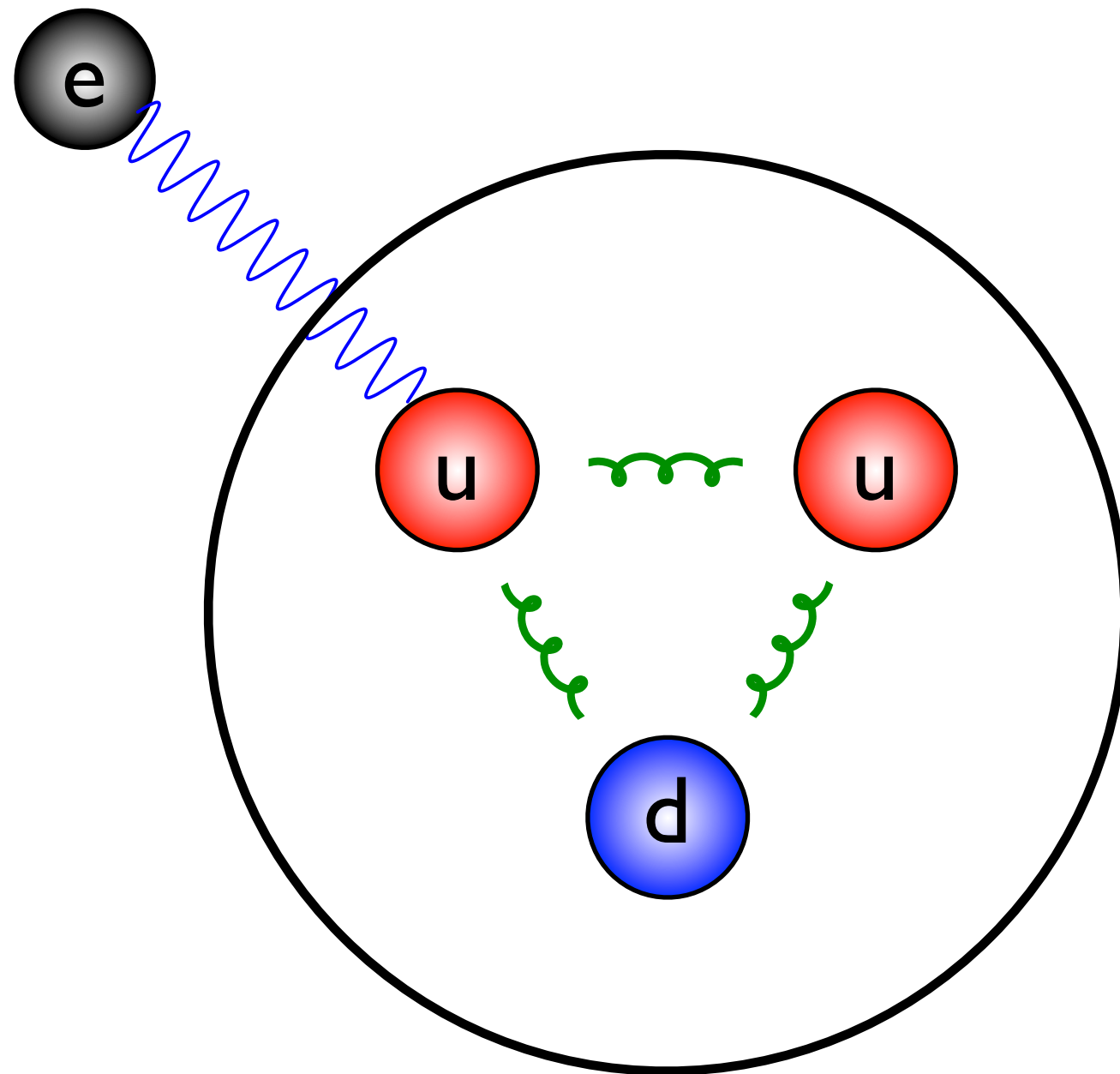


Lepton-Hadron Collisions

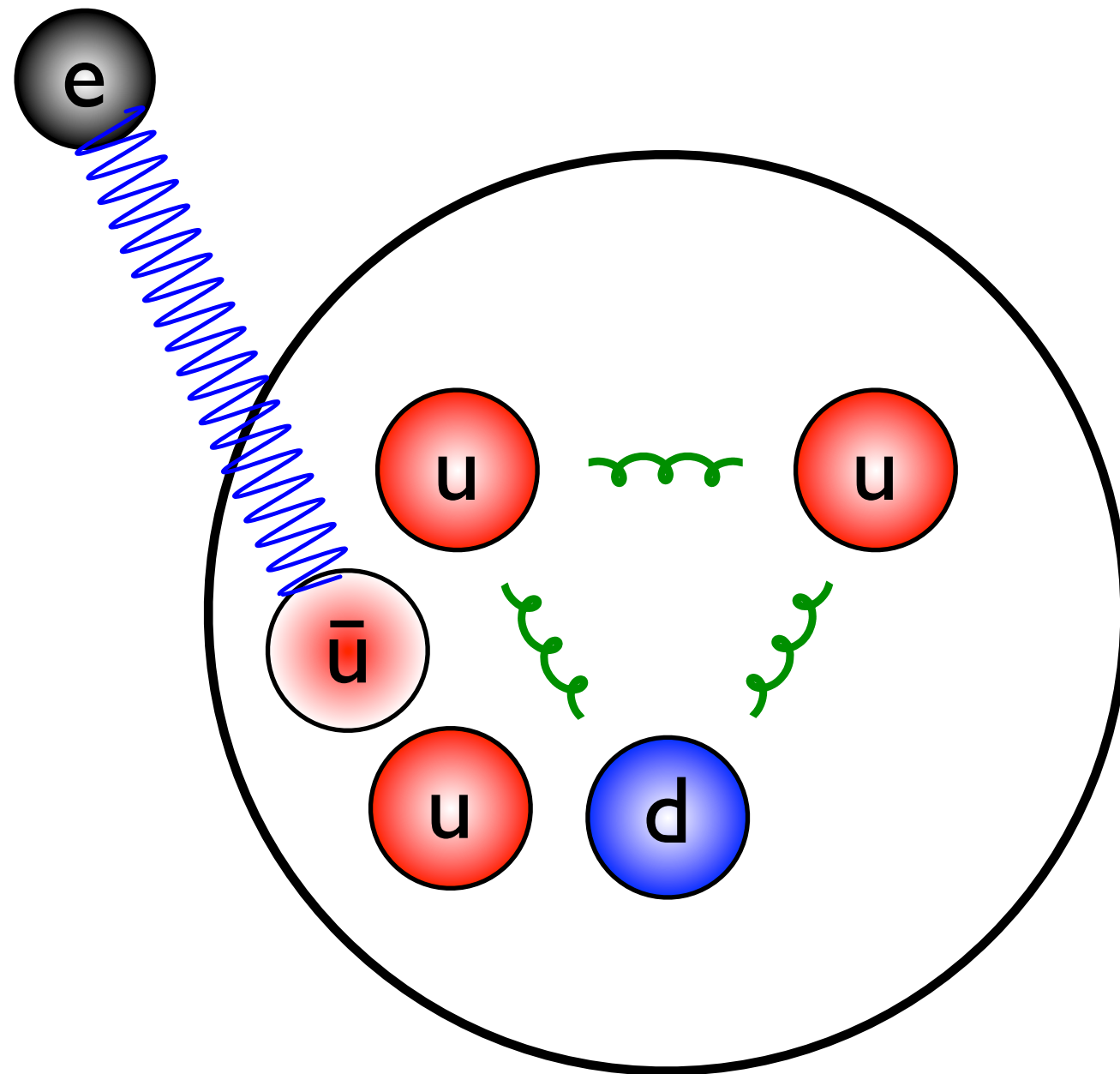
Deep Inelastic Scattering



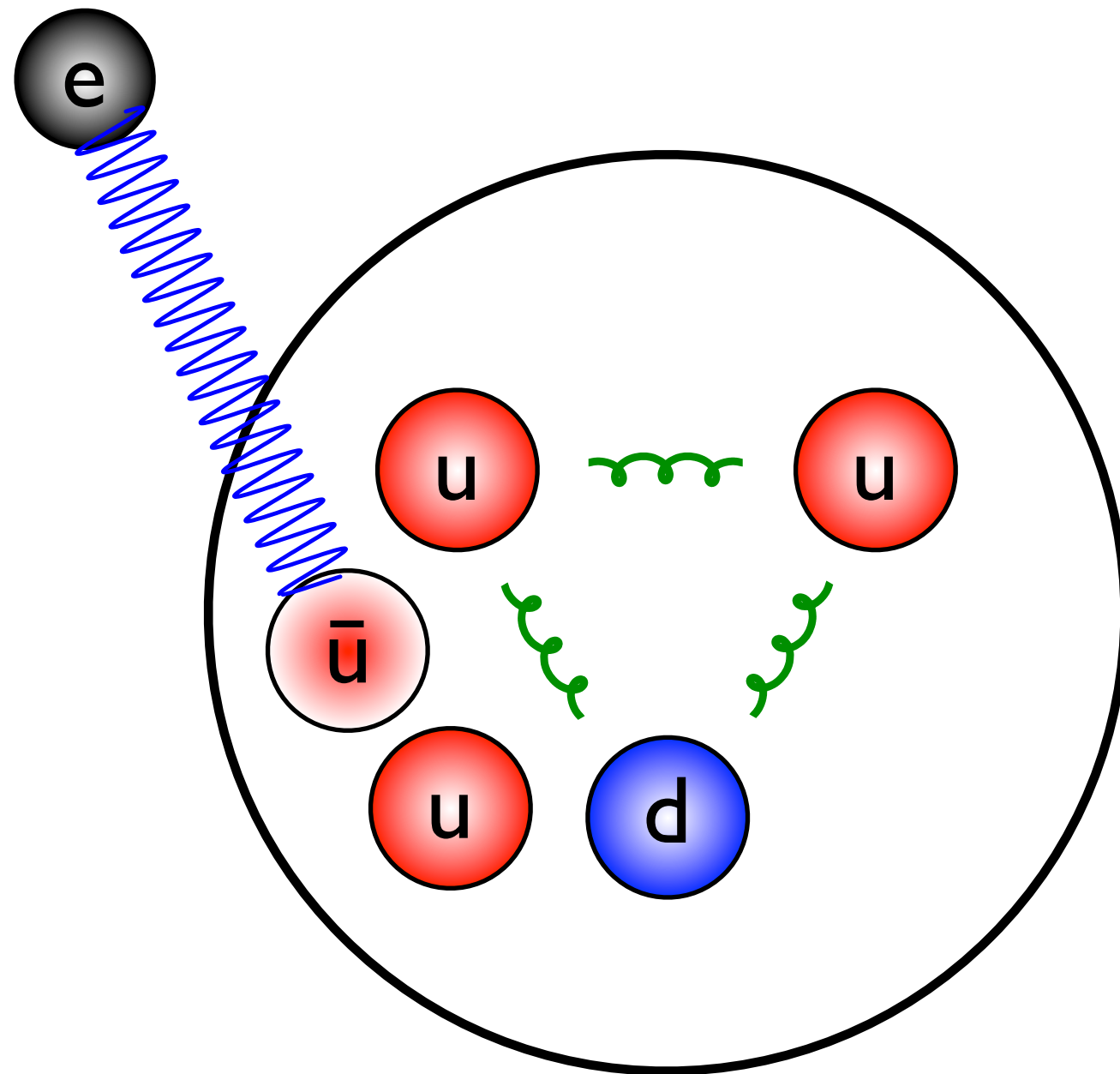
Deep Inelastic Scattering



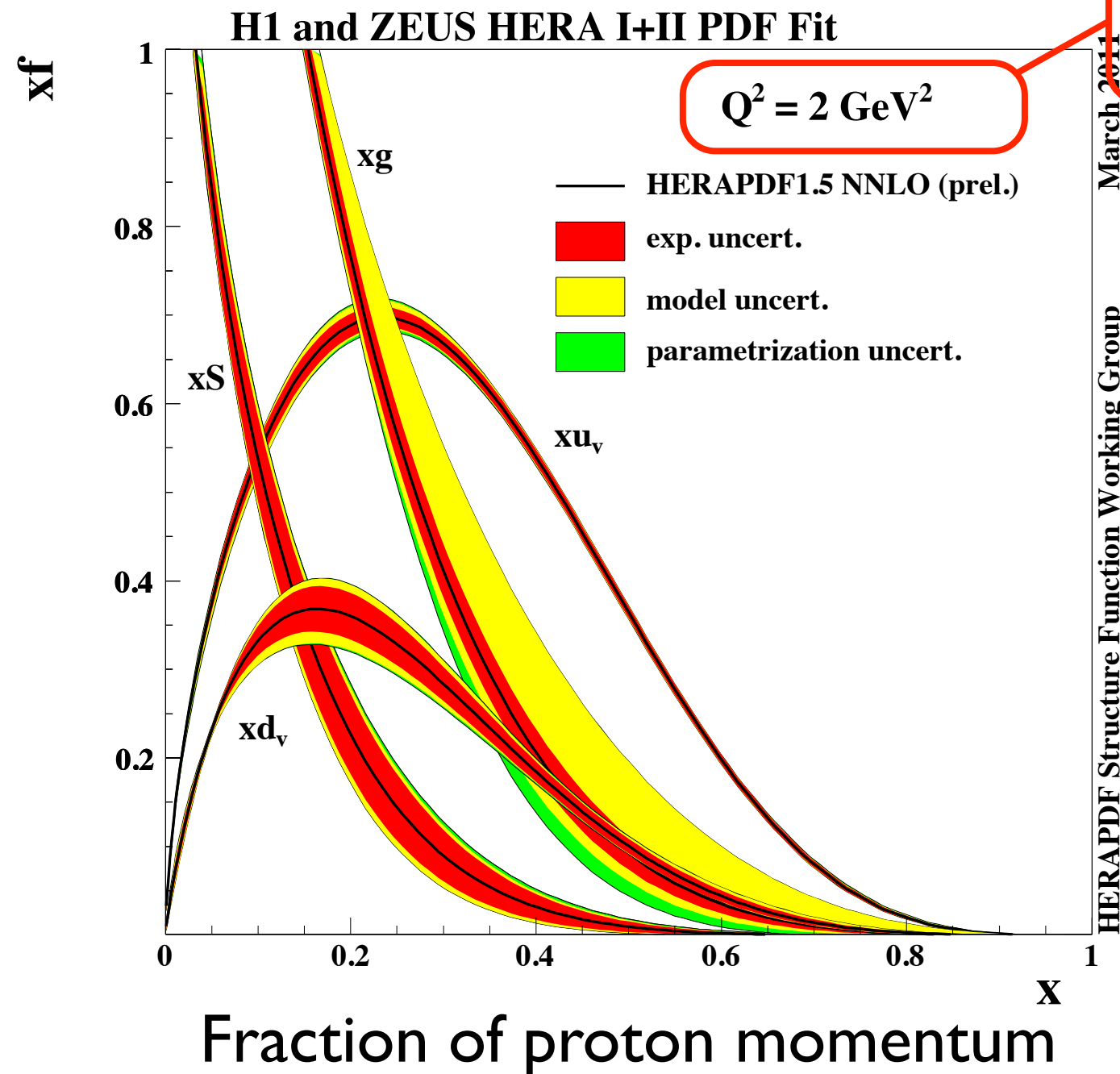
Deep Inelastic Scattering



Deep Inelastic Scattering

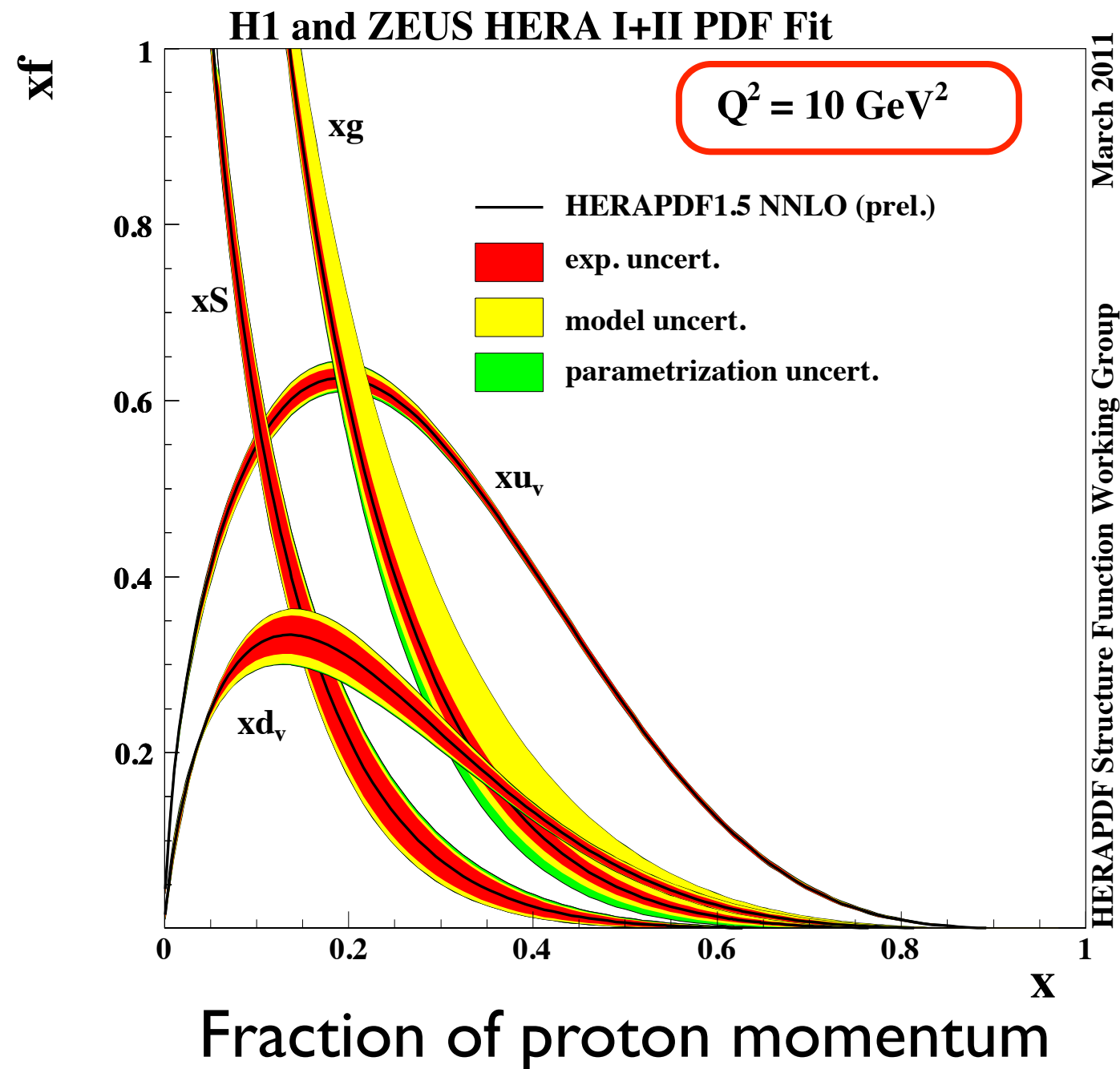


Quark and Gluon (Parton) Distributions

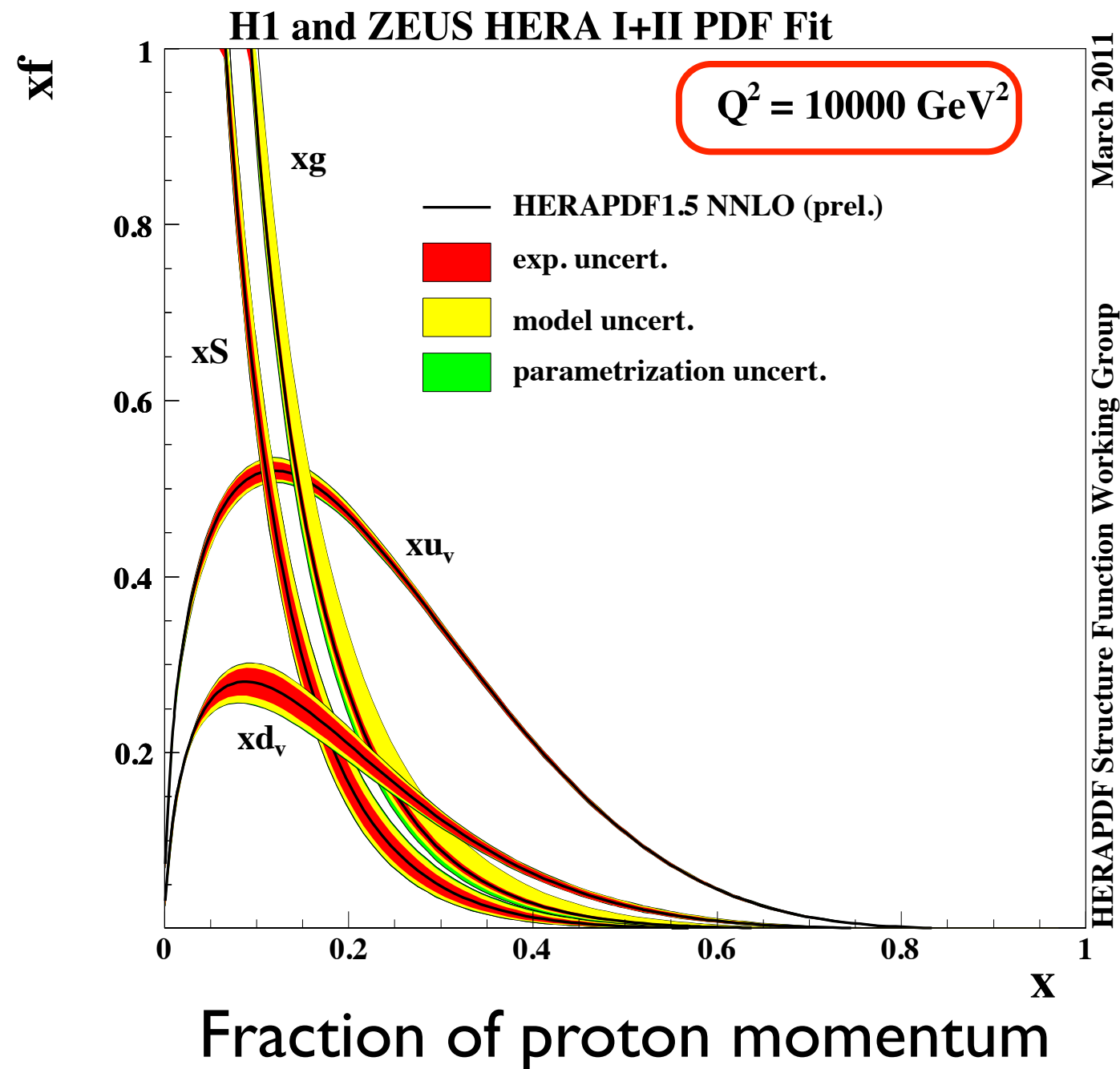


Invariant 4-momentum
transfer squared

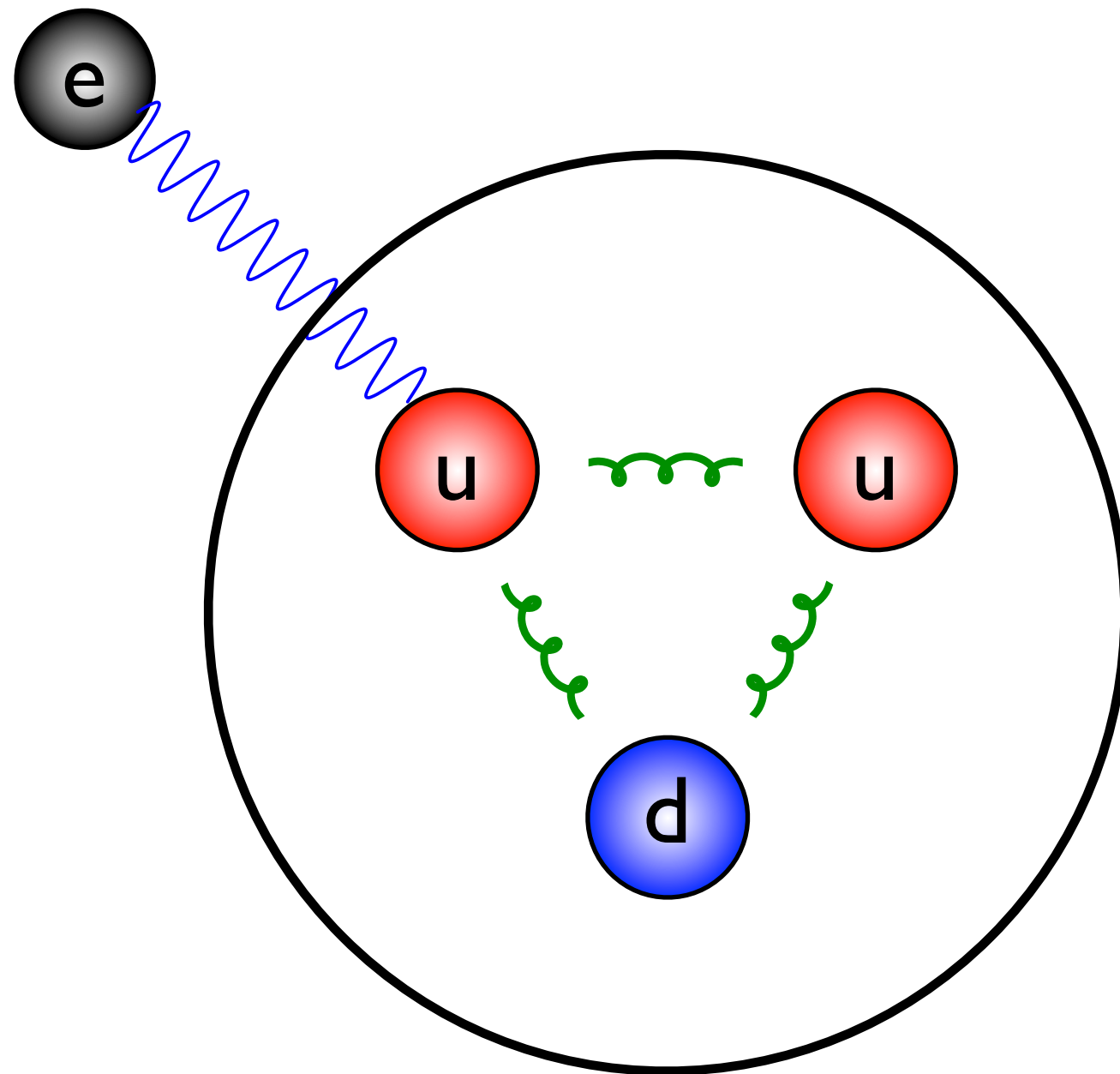
Quark and Gluon (Parton) Distributions



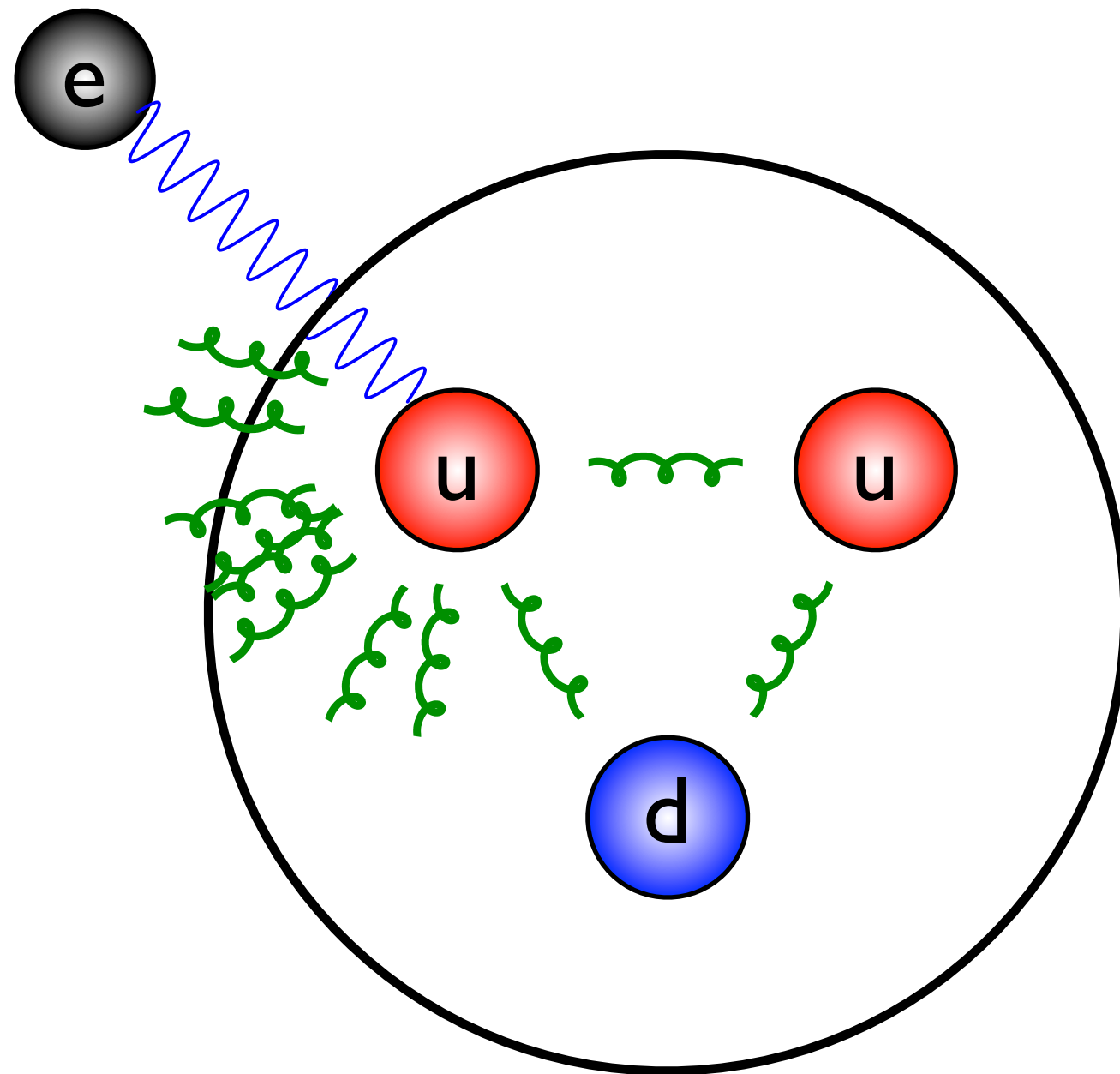
Quark and Gluon (Parton) Distributions



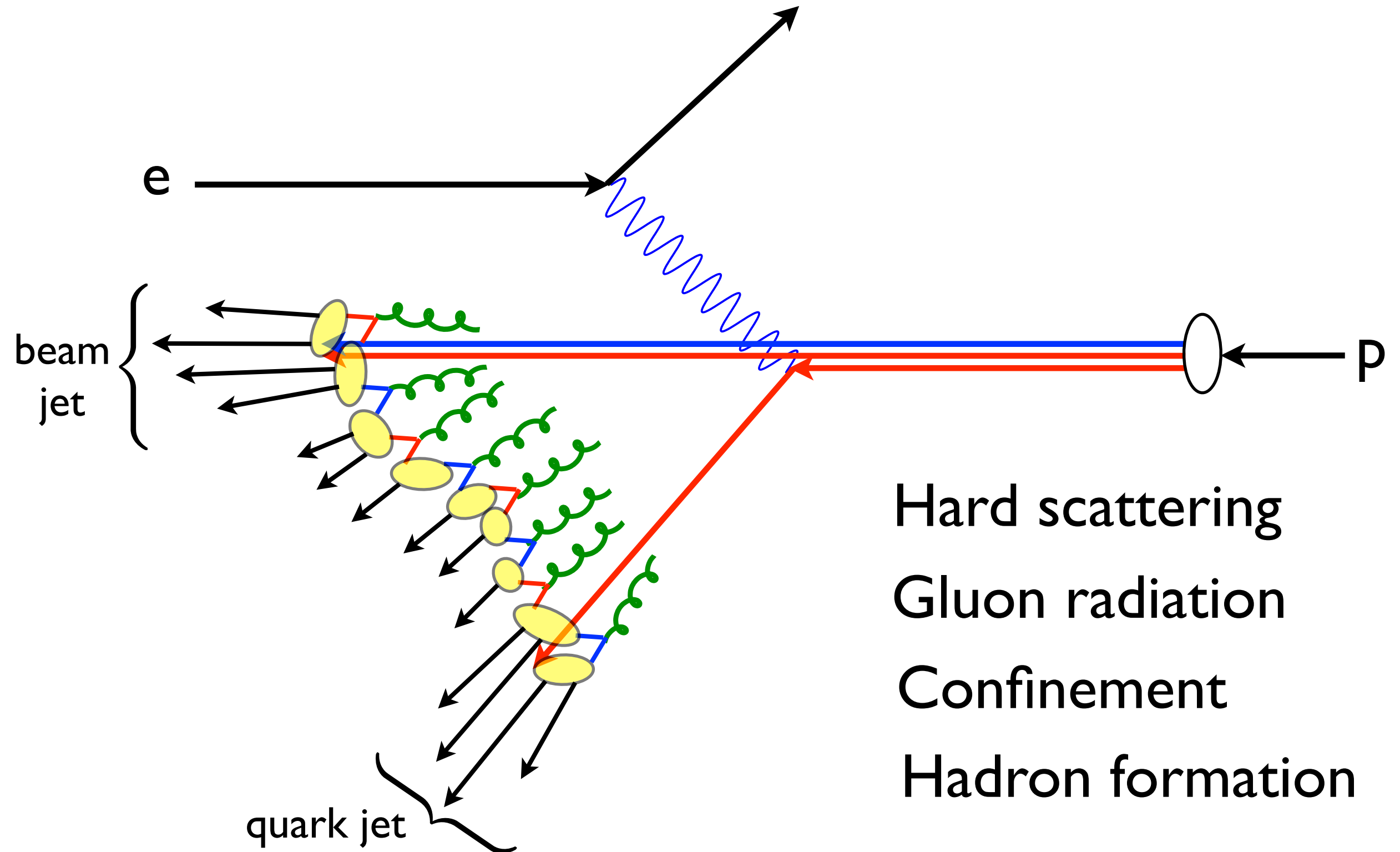
Deep Inelastic Scattering



Deep Inelastic Scattering



Deep Inelastic Scattering

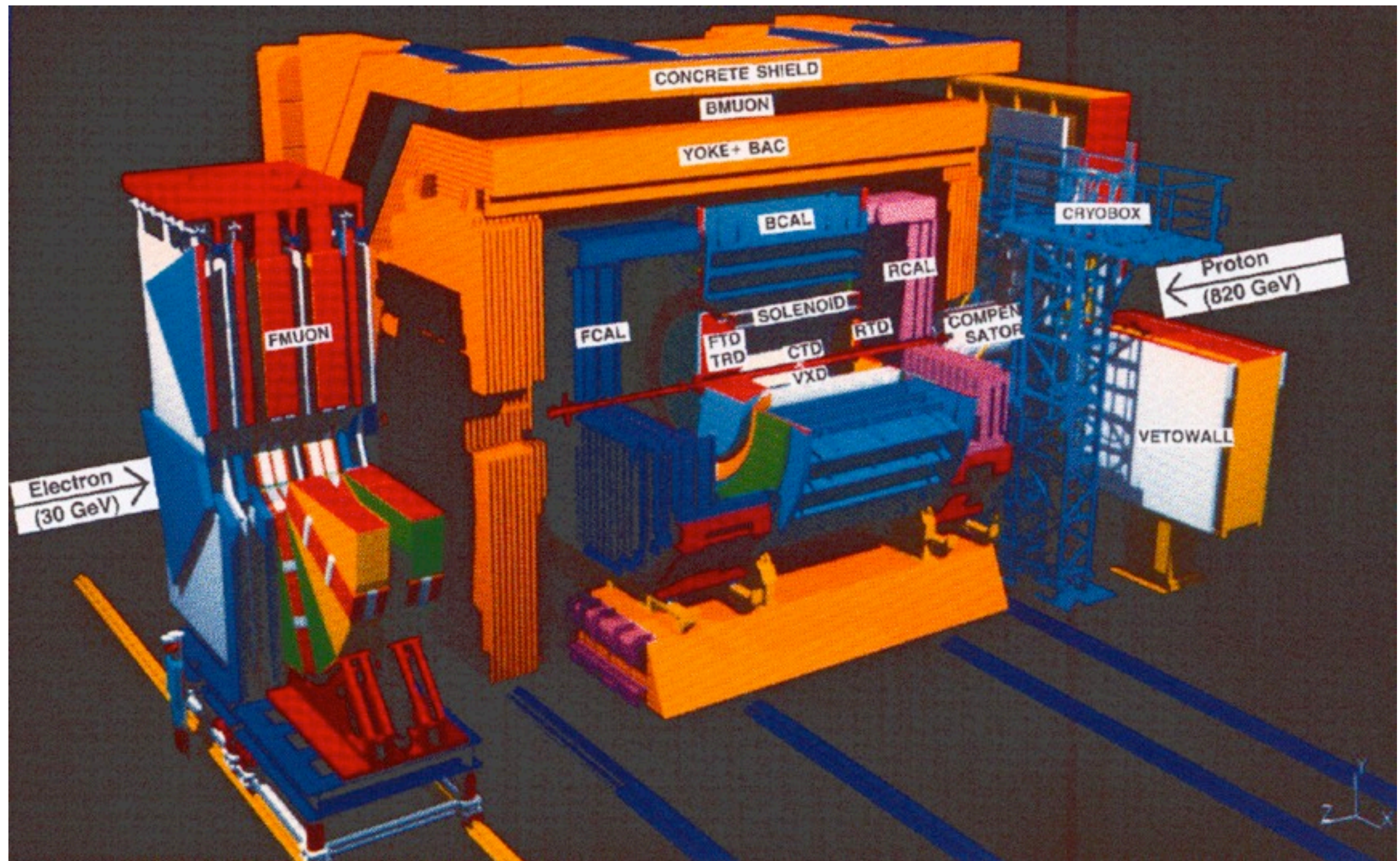


HERA ep Collider

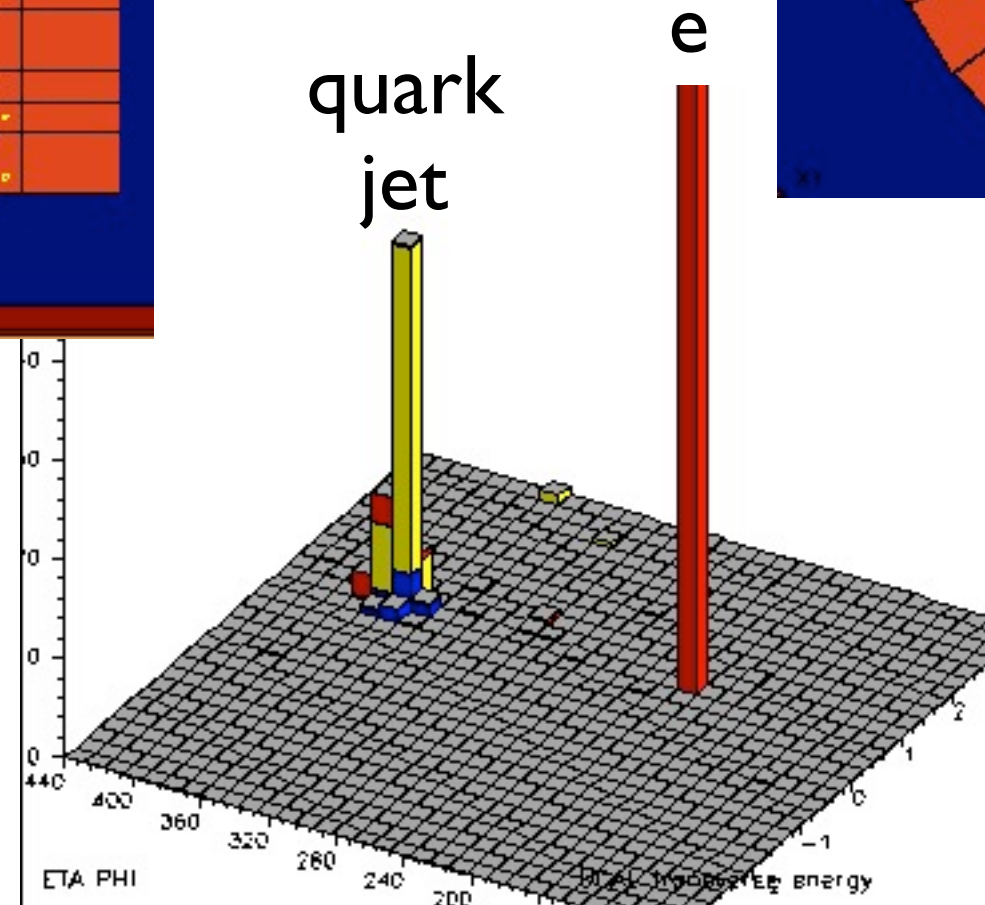
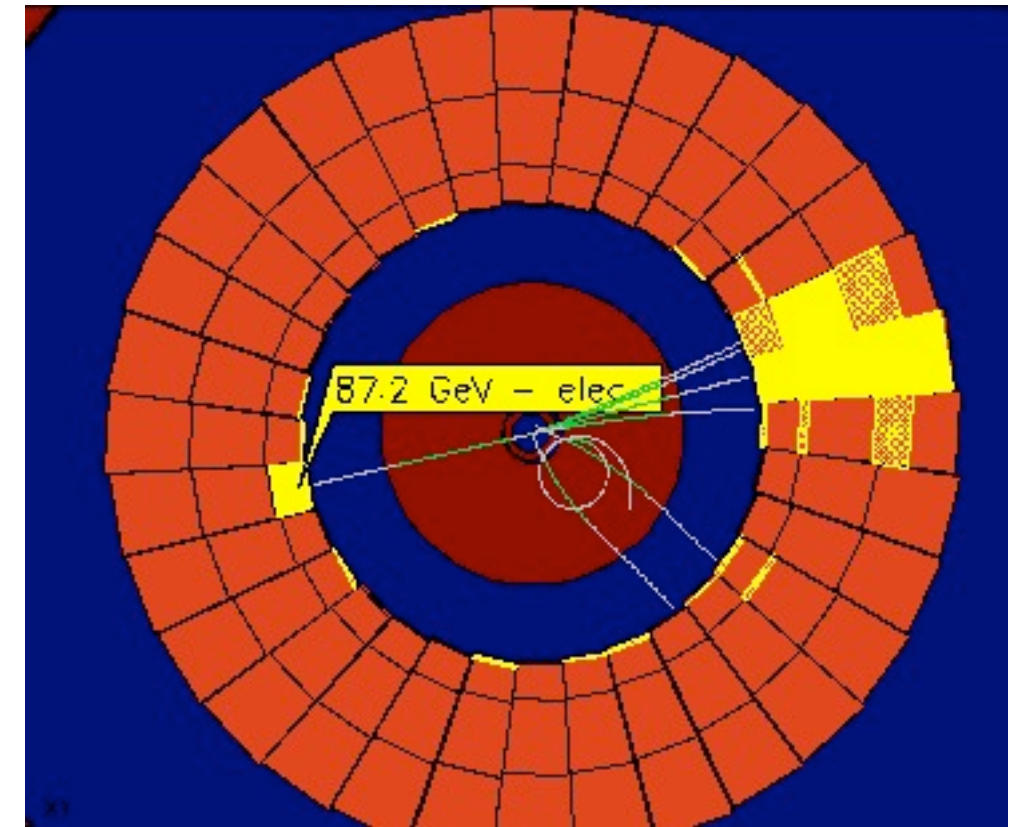
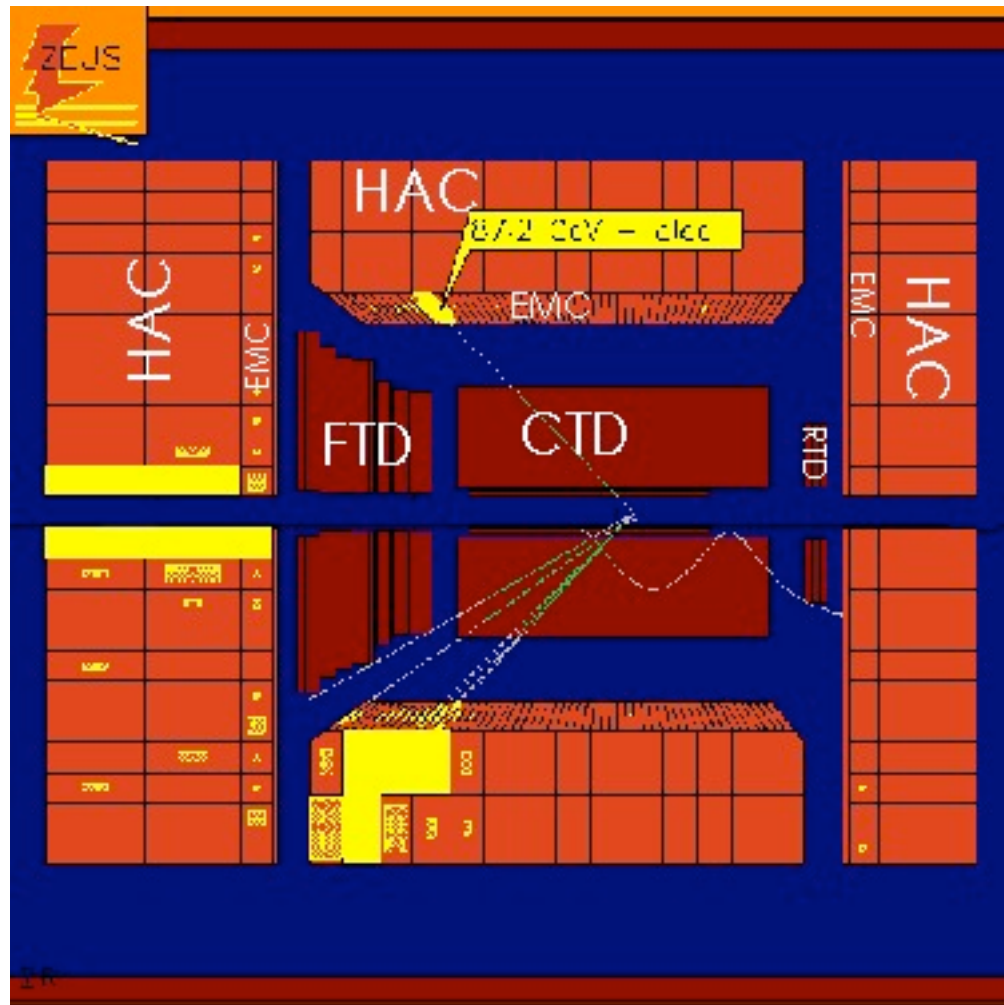


- Located at DESY Hamburg
- Electron-proton collisions at 318 GeV ($M_{pc^2} \sim 1 \text{ GeV}$)
- Main experiments H1 and ZEUS
- Closed June 2007

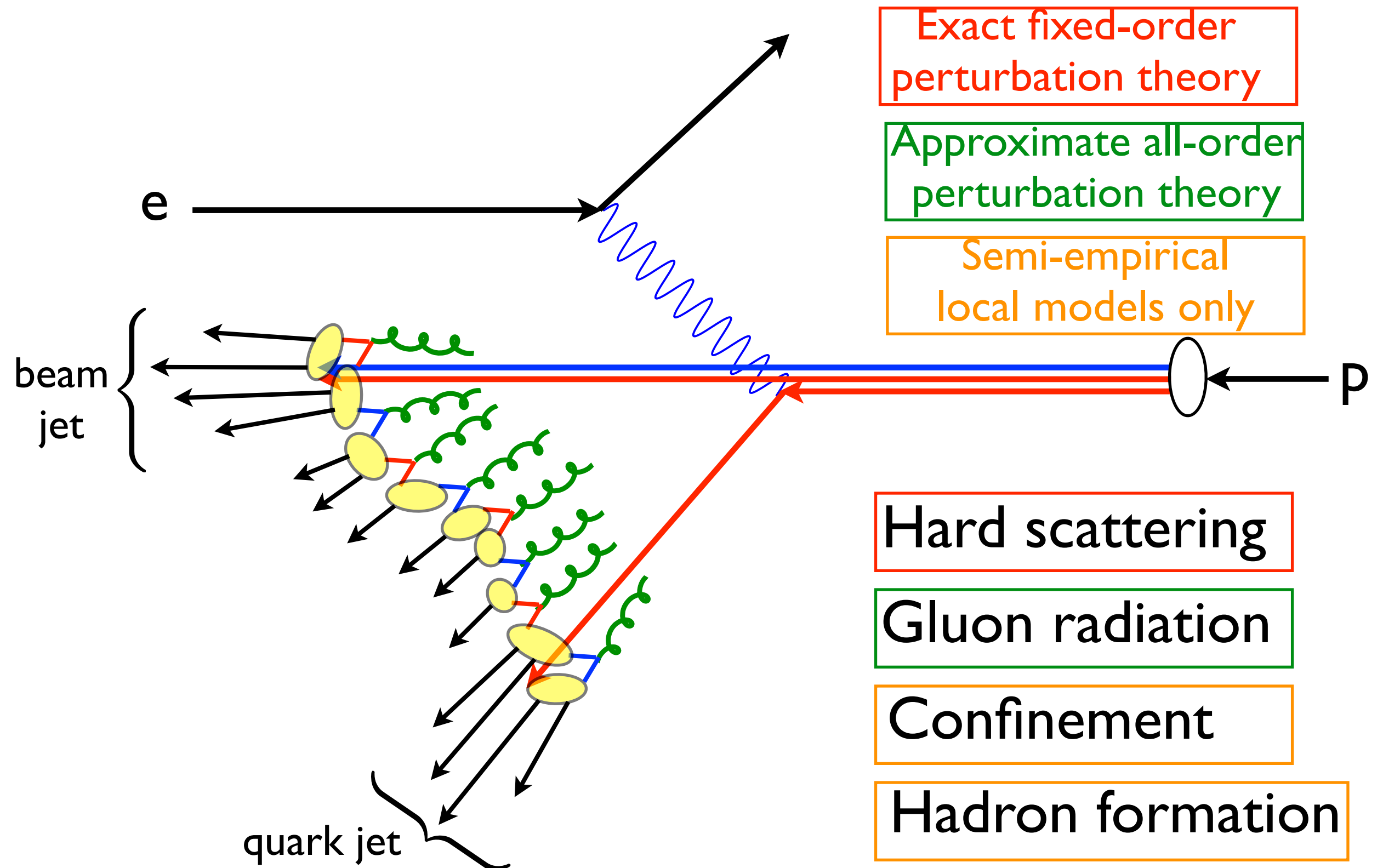
ZEUS Detector



ZEUS Event Display



Theoretical Status



Hadron-Hadron Collisions

Tevatron Collider



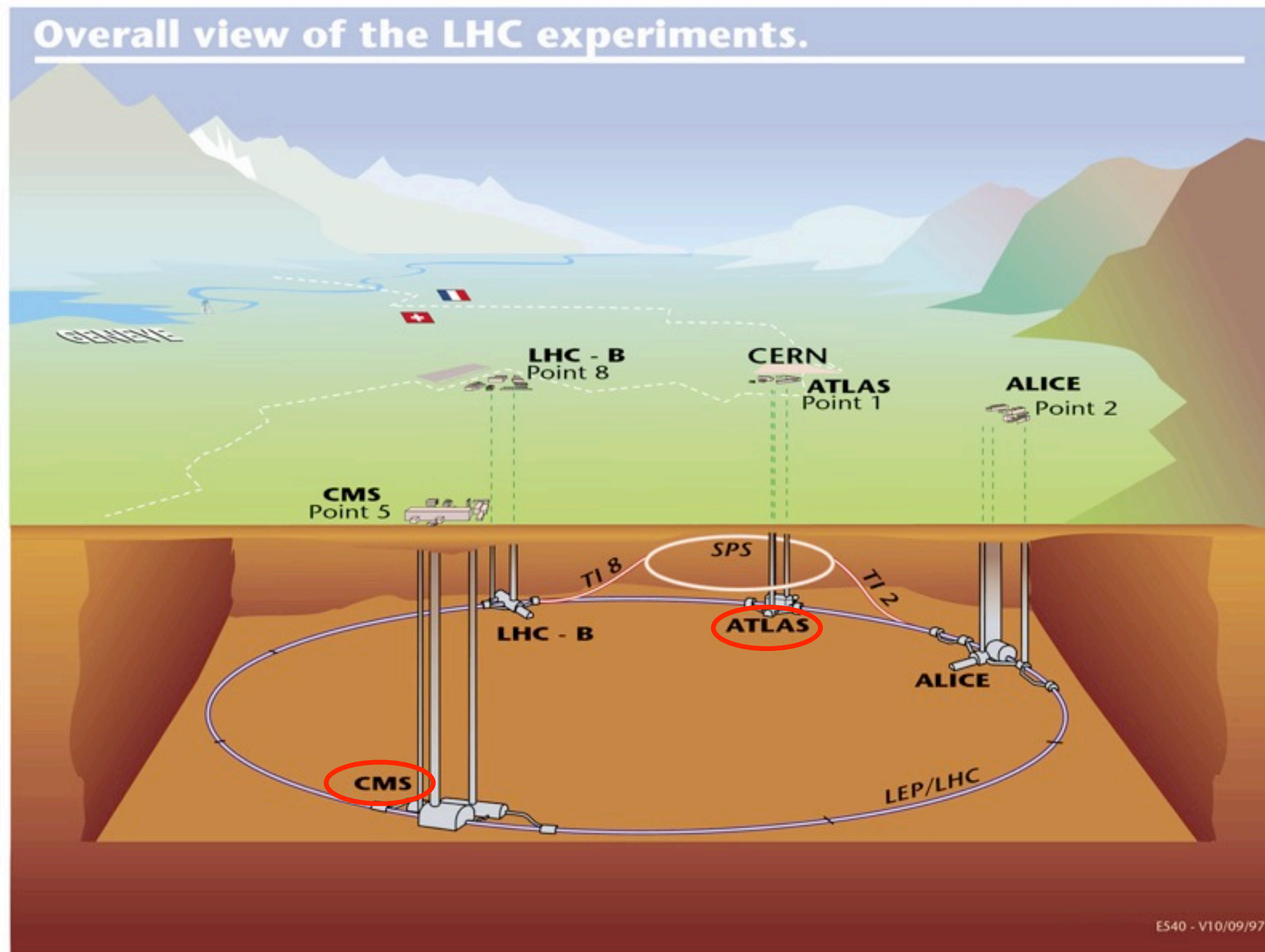
- Located at Fermilab near Chicago
- Proton-antiproton collisions at 1.96 TeV
- Main experiments CDF and D0
- Closed September 2011

Large Hadron Collider



- Located at CERN near Geneva
- Proton-proton collisions at 7 TeV (2011), 8 TeV (2012)
- Main experiments ATLAS and CMS
- Design energy 14 TeV

LHC Experiments



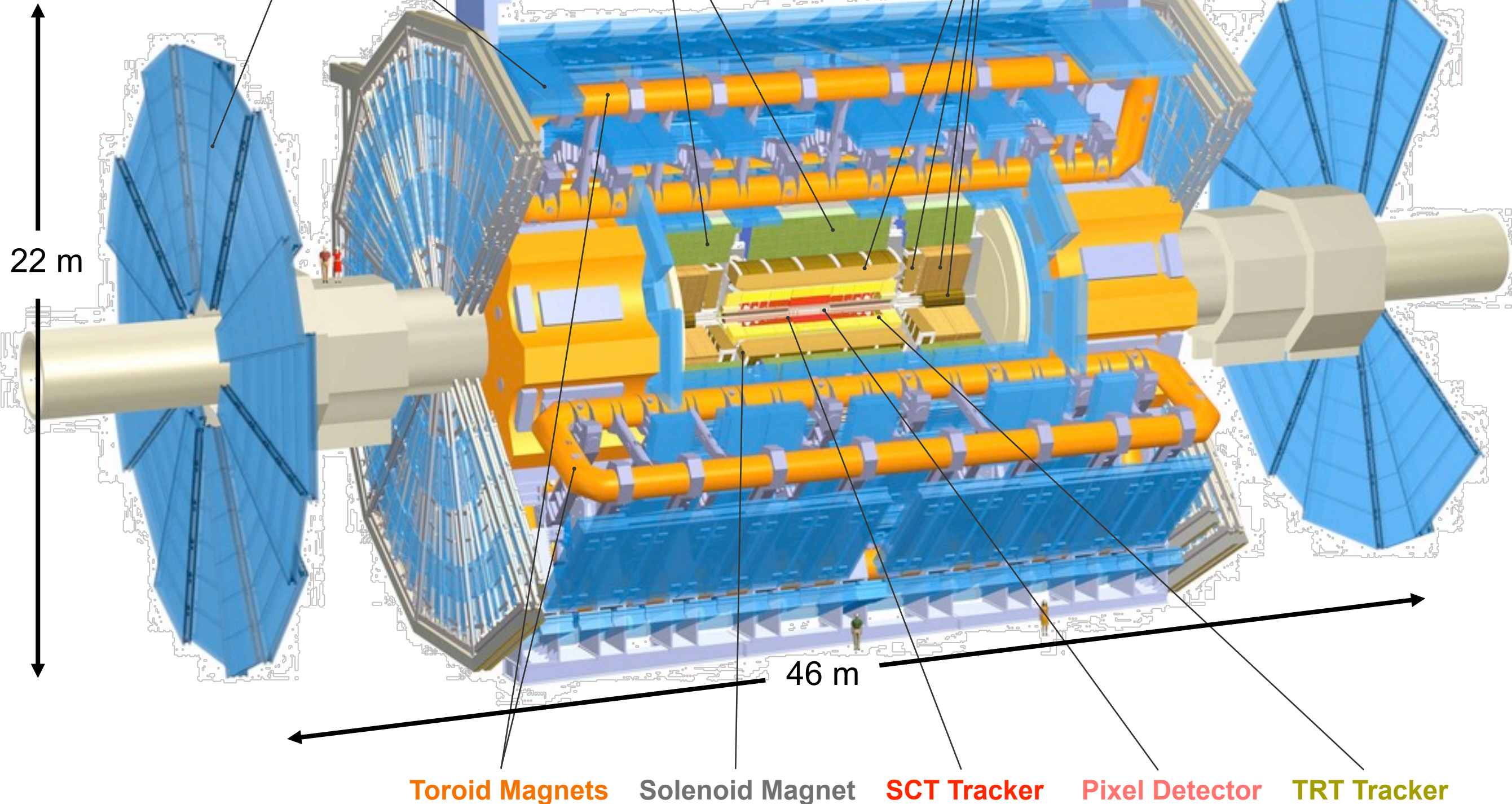
A Toroidal LHC Apparatus



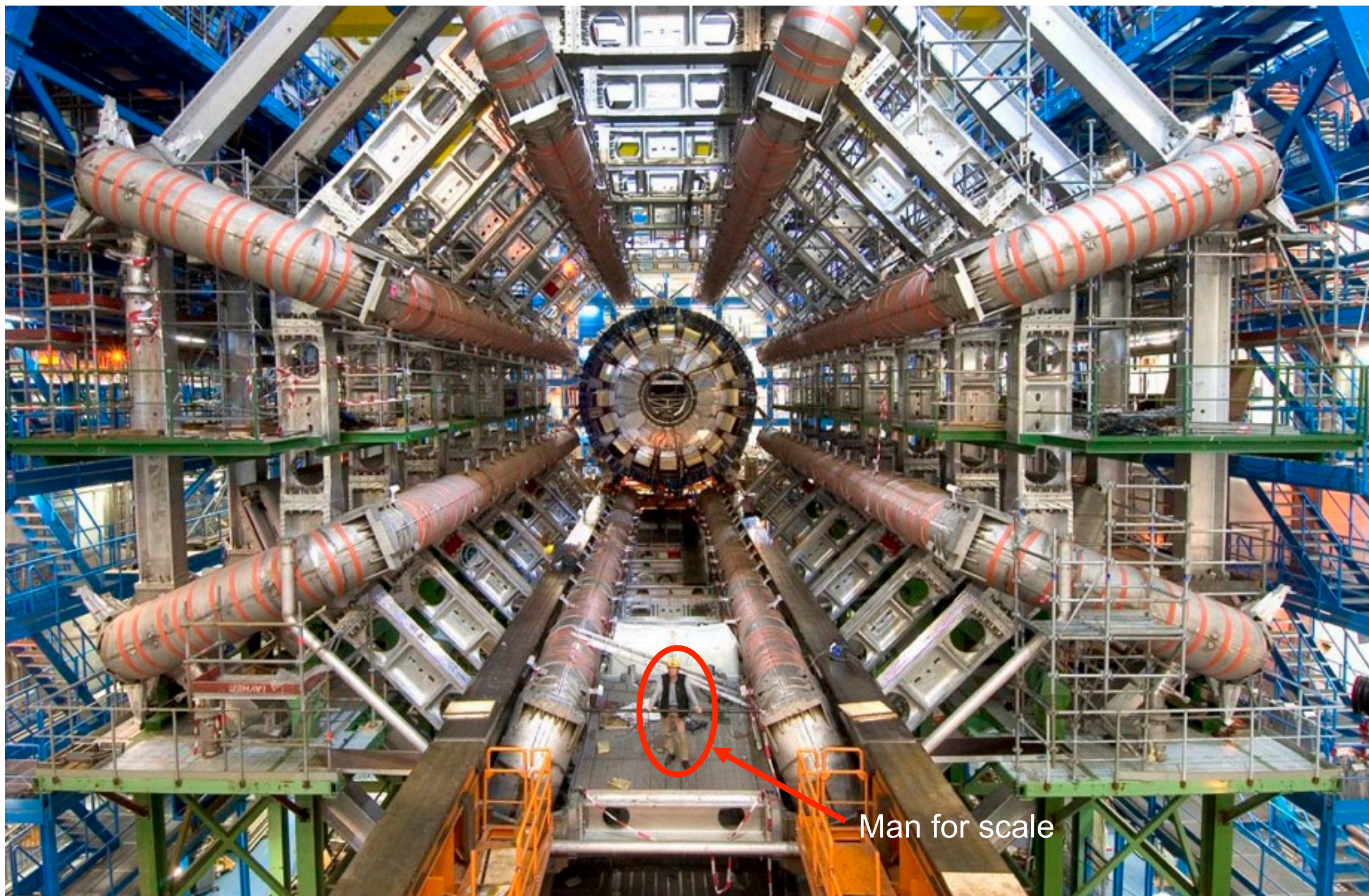
Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeters

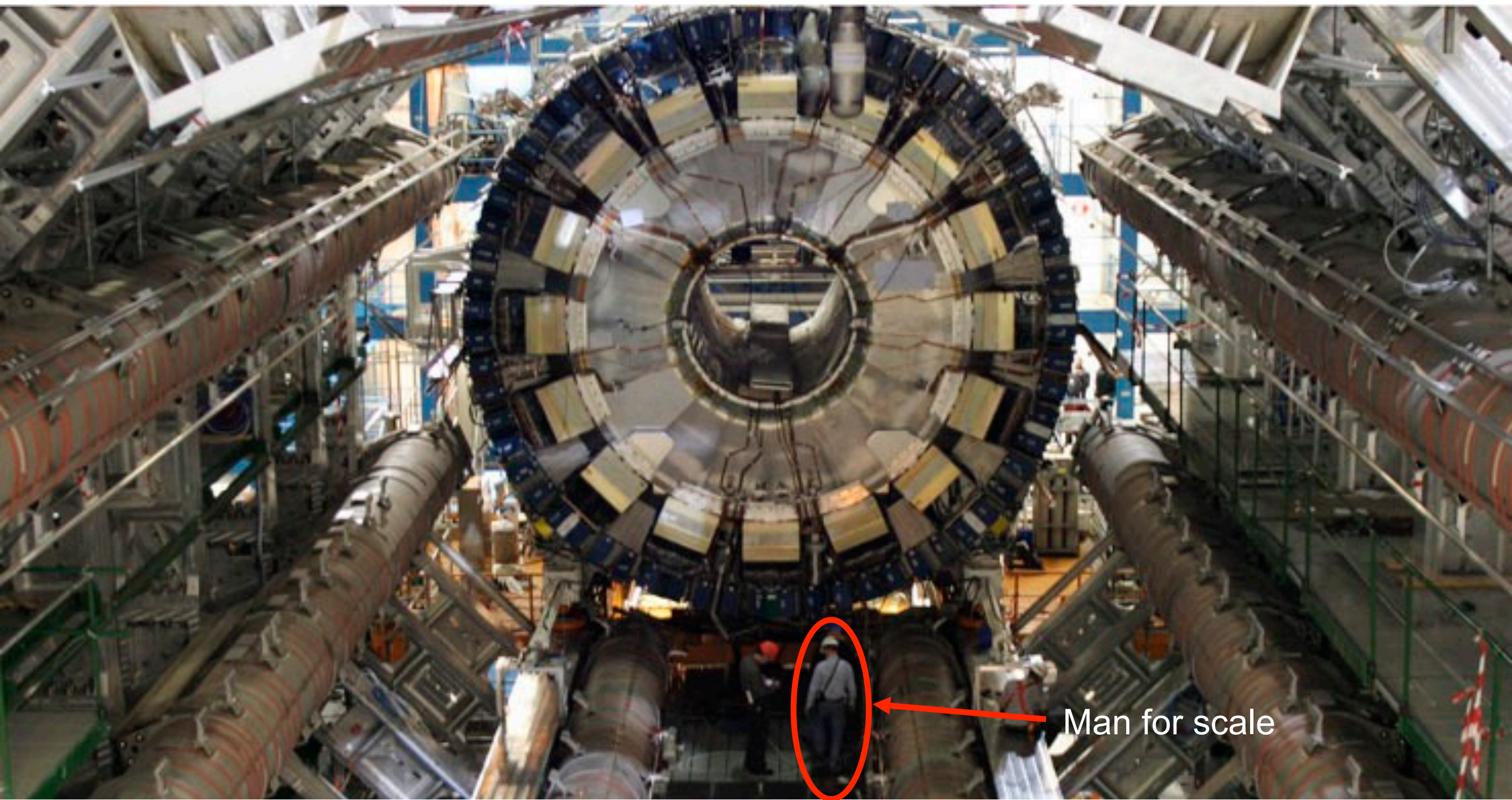


ATLAS Muon Detector

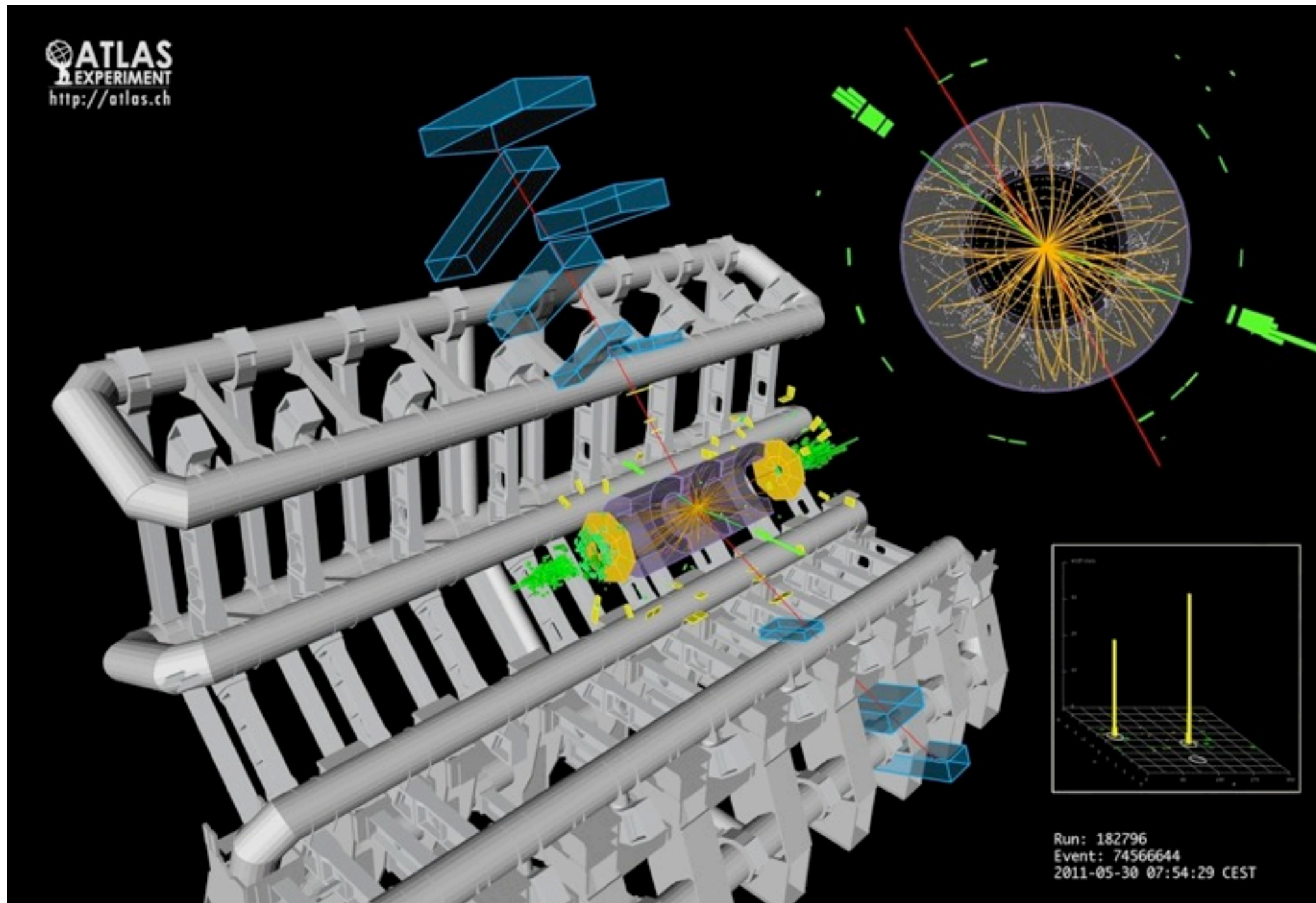


Man for scale

ATLAS Calorimeters and Central Solenoid

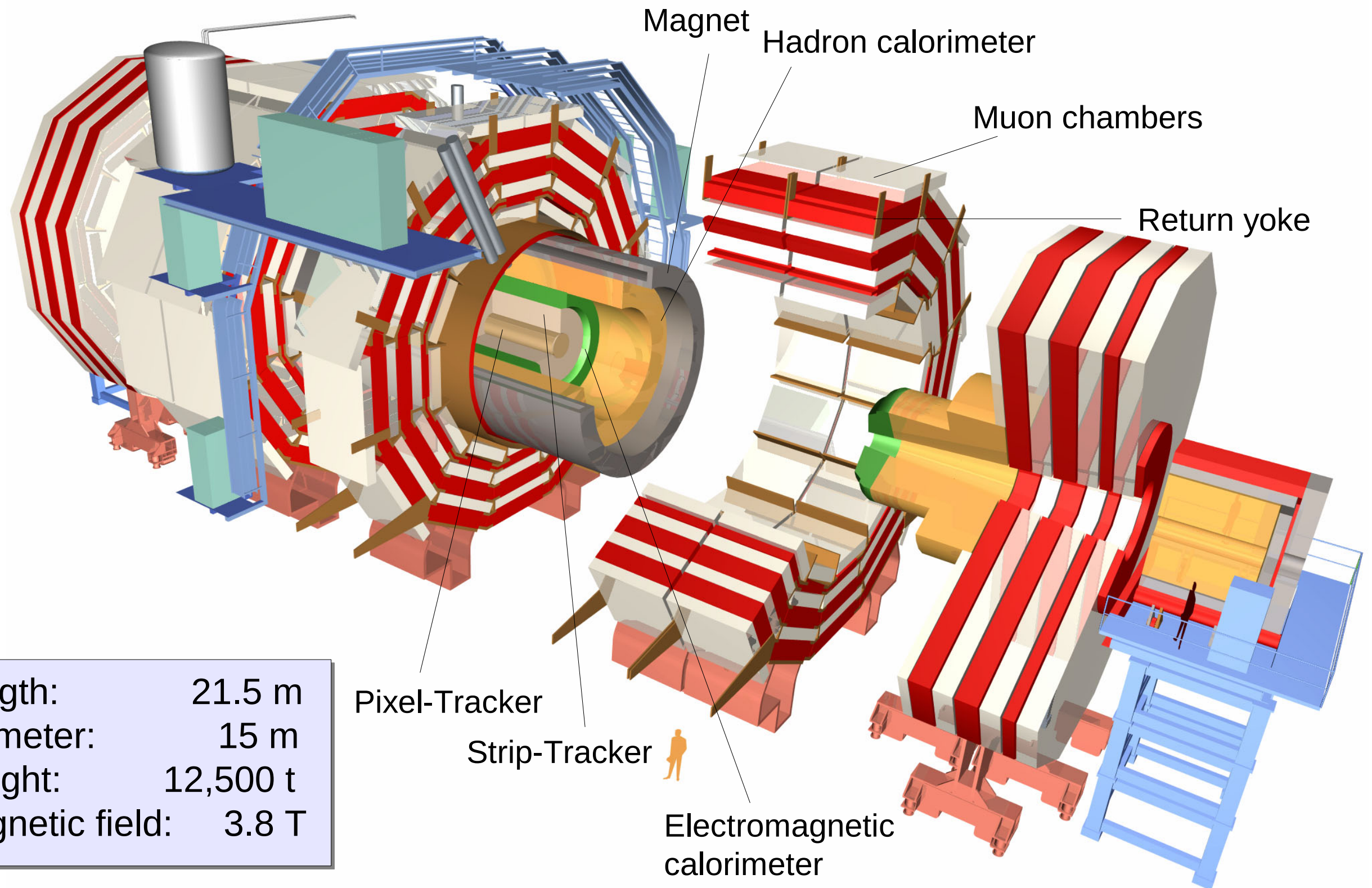


ATLAS Event Display

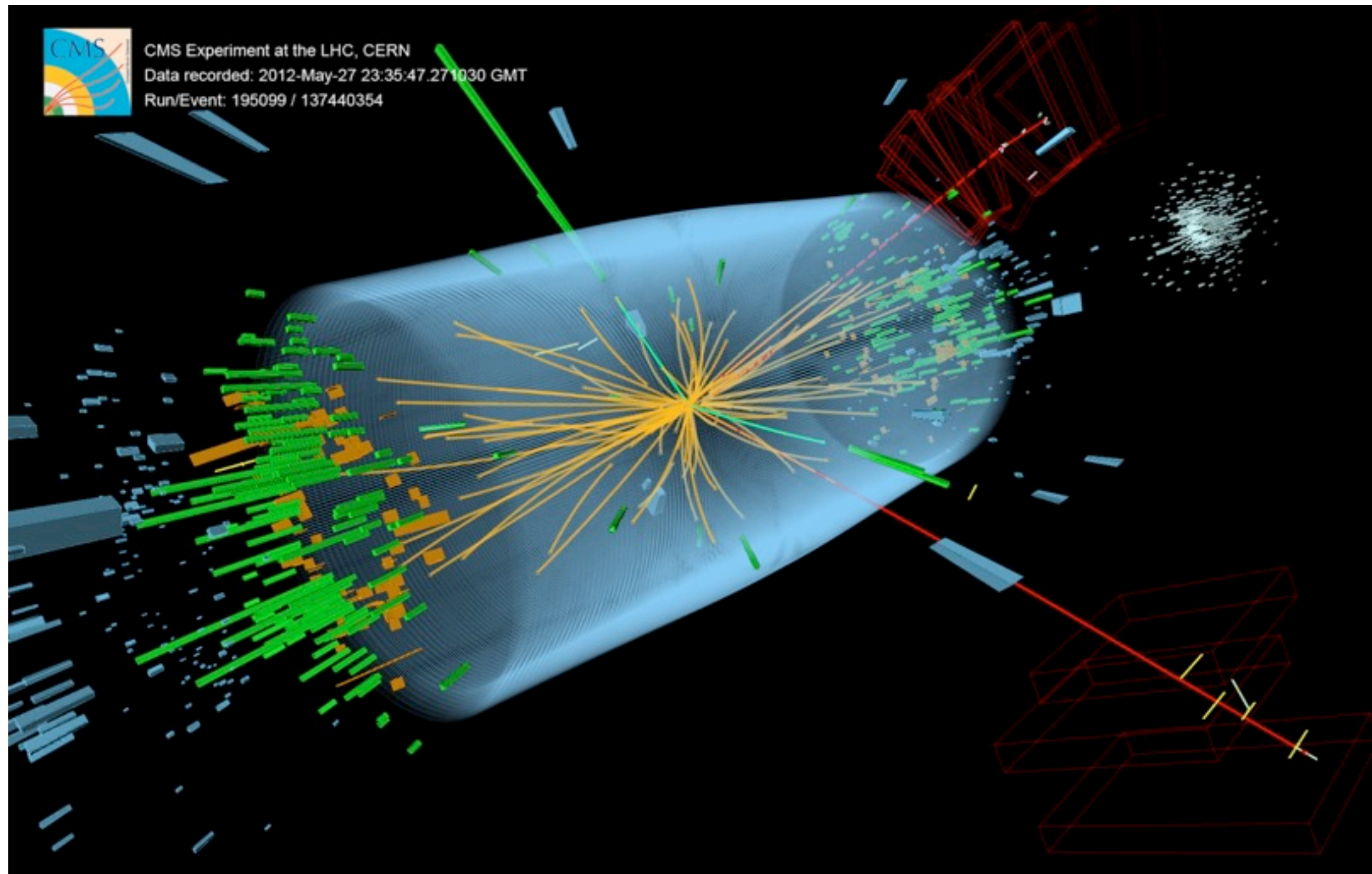


- Candidate for Higgs decay to $e^+e^-\mu^+\mu^-$

Compact Muon Solenoid

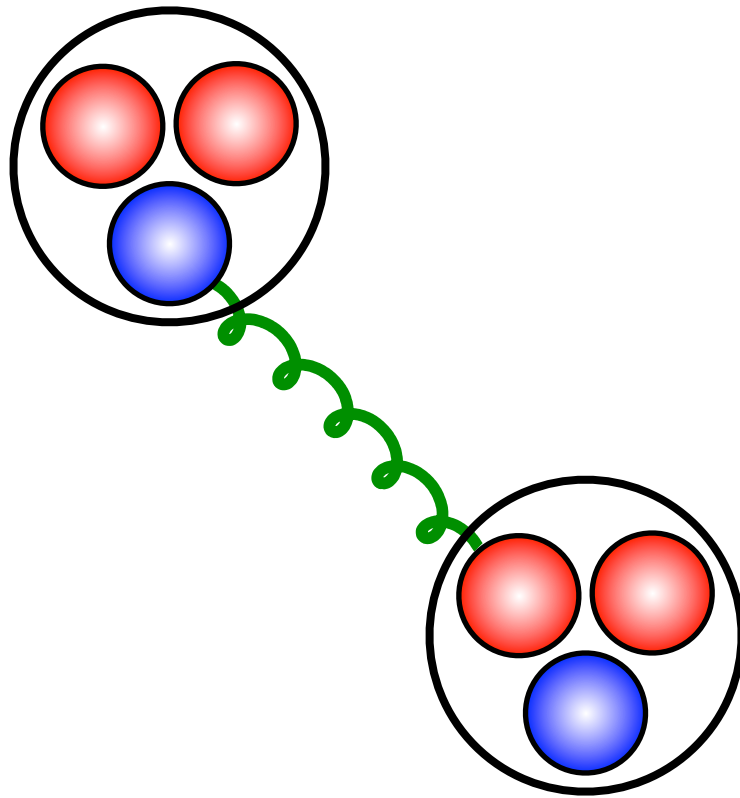


CMS Event Display

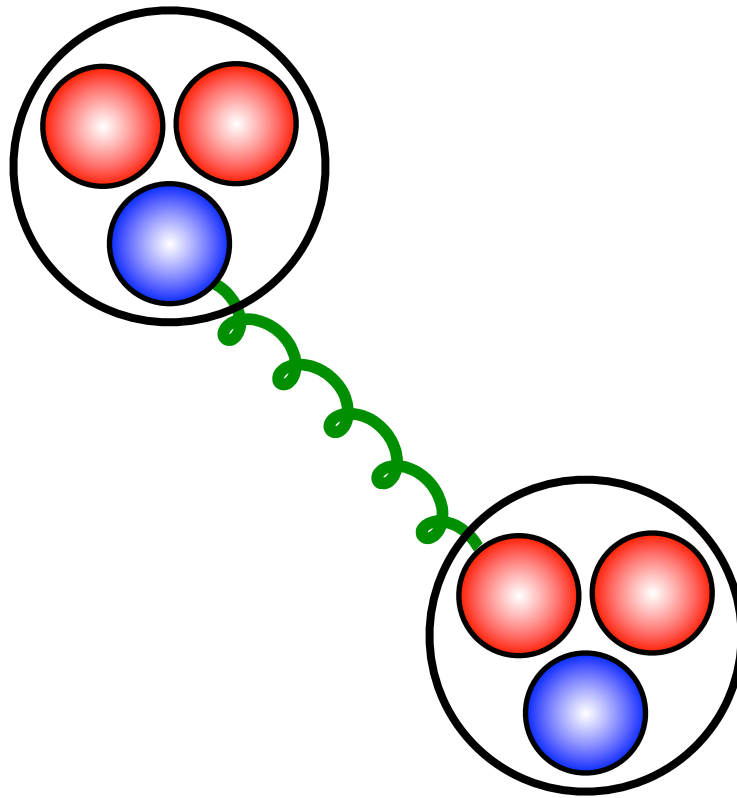


- Candidate for Higgs decay to $e^+e^-\mu^+\mu^-$

LHC Collision

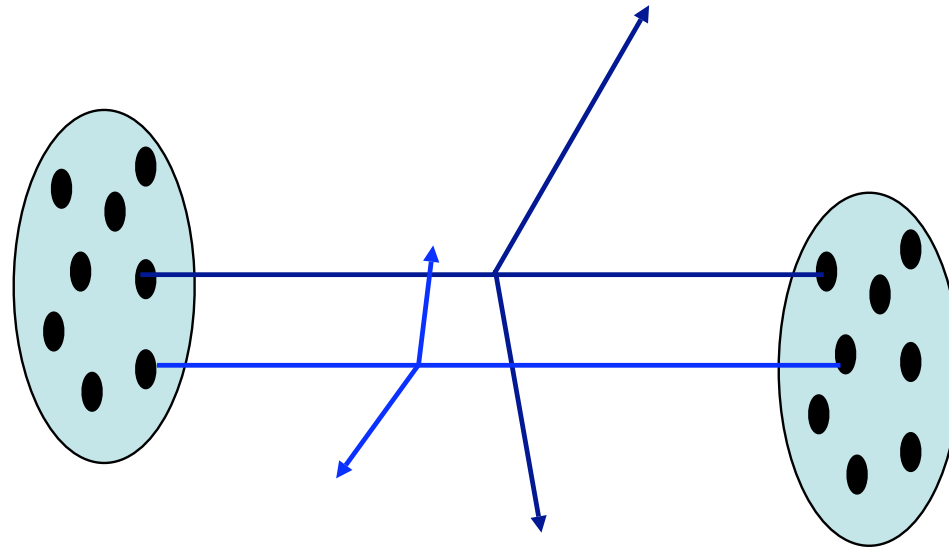


LHC Collision



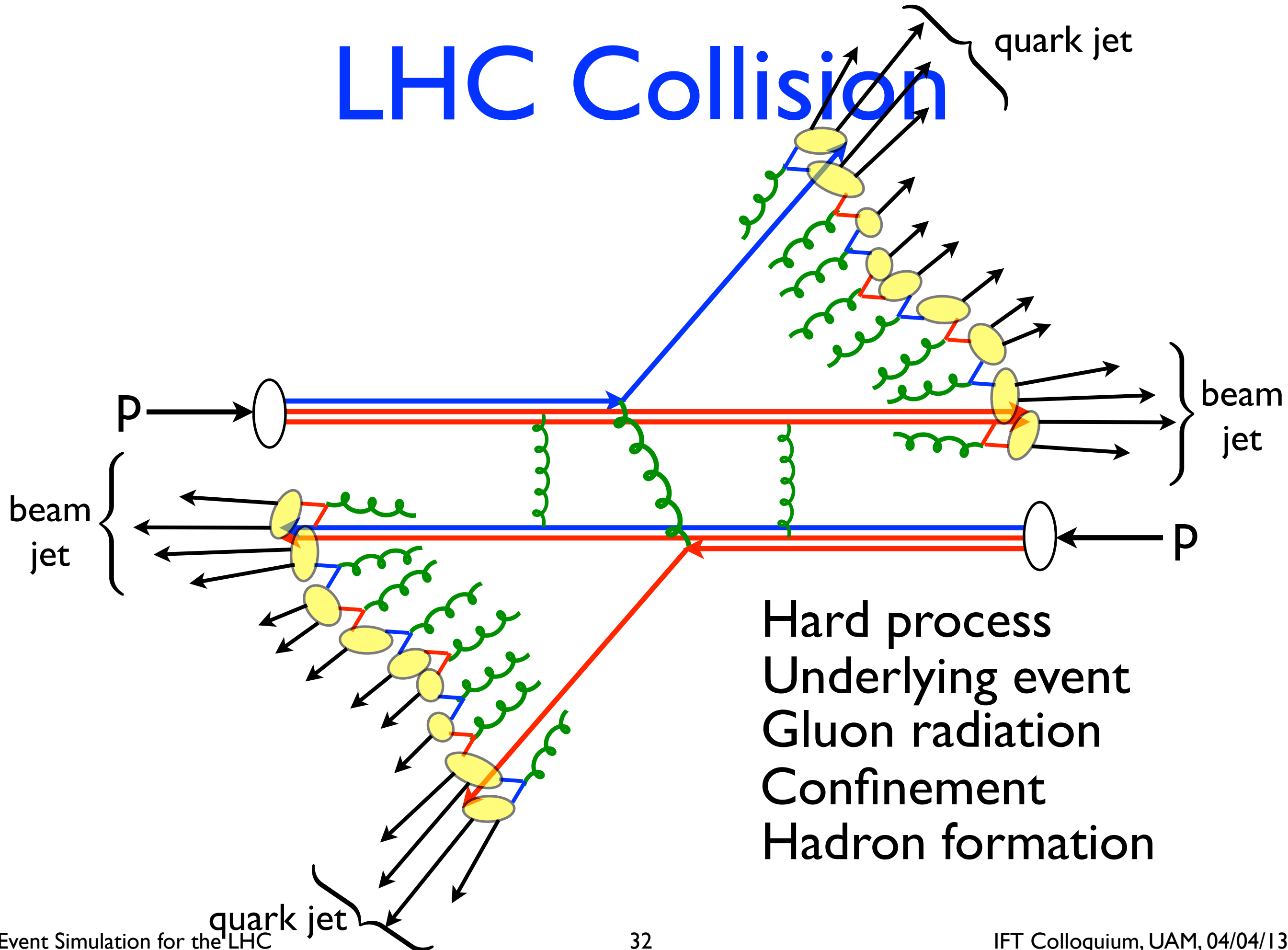
Dijet production

Multiple Interactions

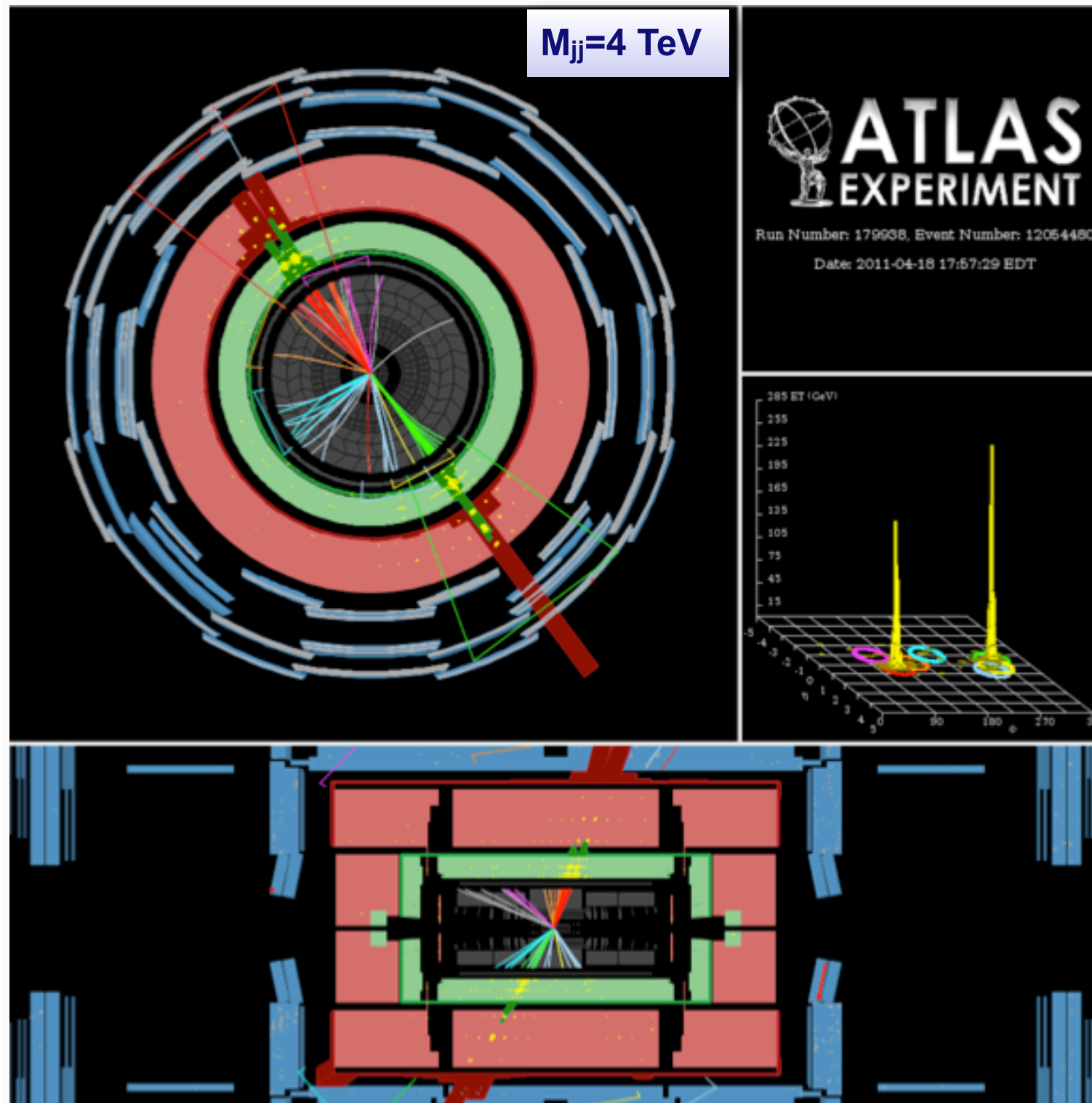


- A feature of hadron-hadron collisions, not present in lepton-lepton or lepton-hadron:
 - ✦ Multiple parton interactions in same collision
- These give rise to extra hadron production
 - ✦ Often called the **underlying event**
 - ✦ Not to be confused with **pile-up** (multiple proton collisions in same bunches)

LHC Collision



A high-mass dijet



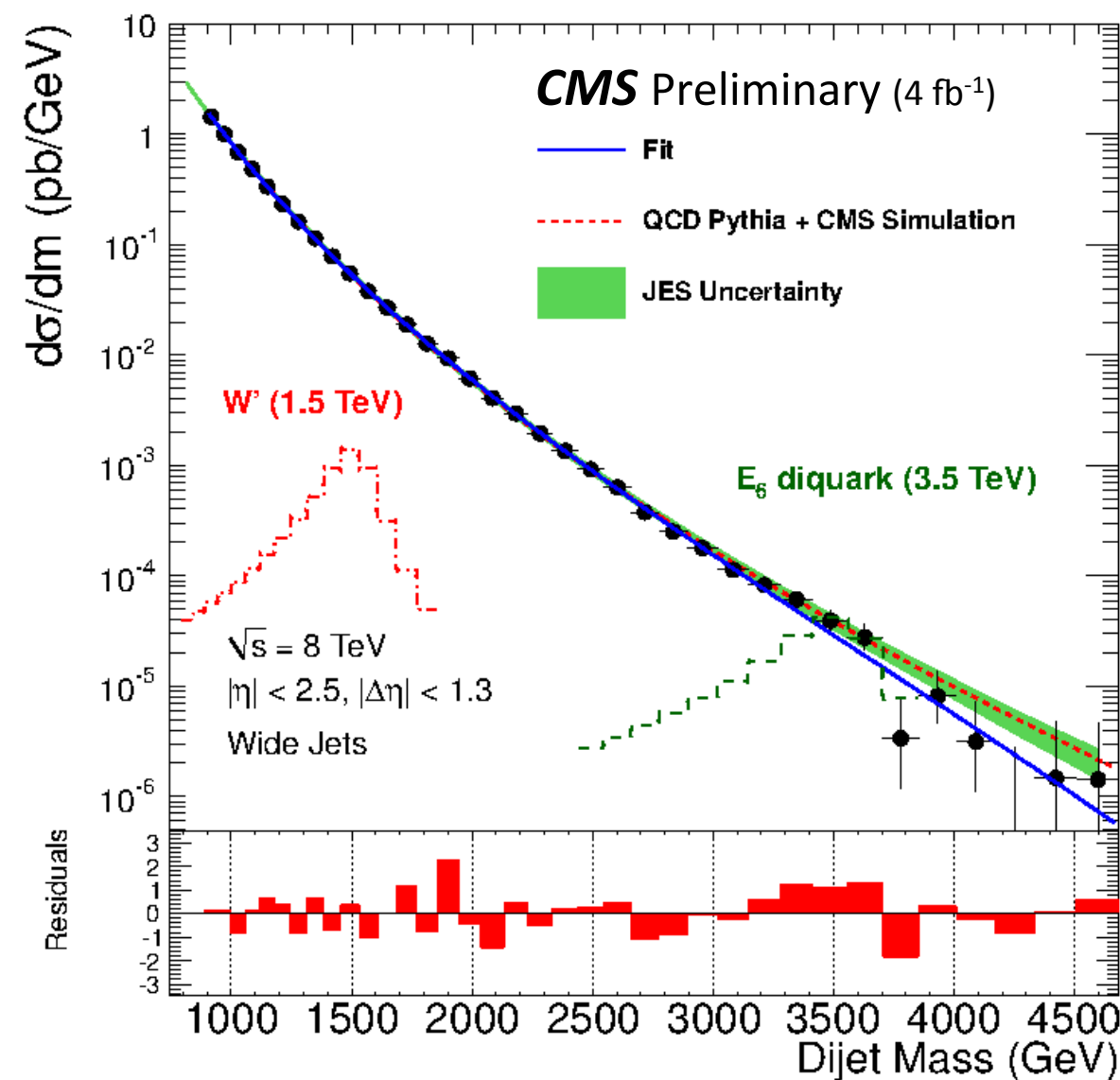
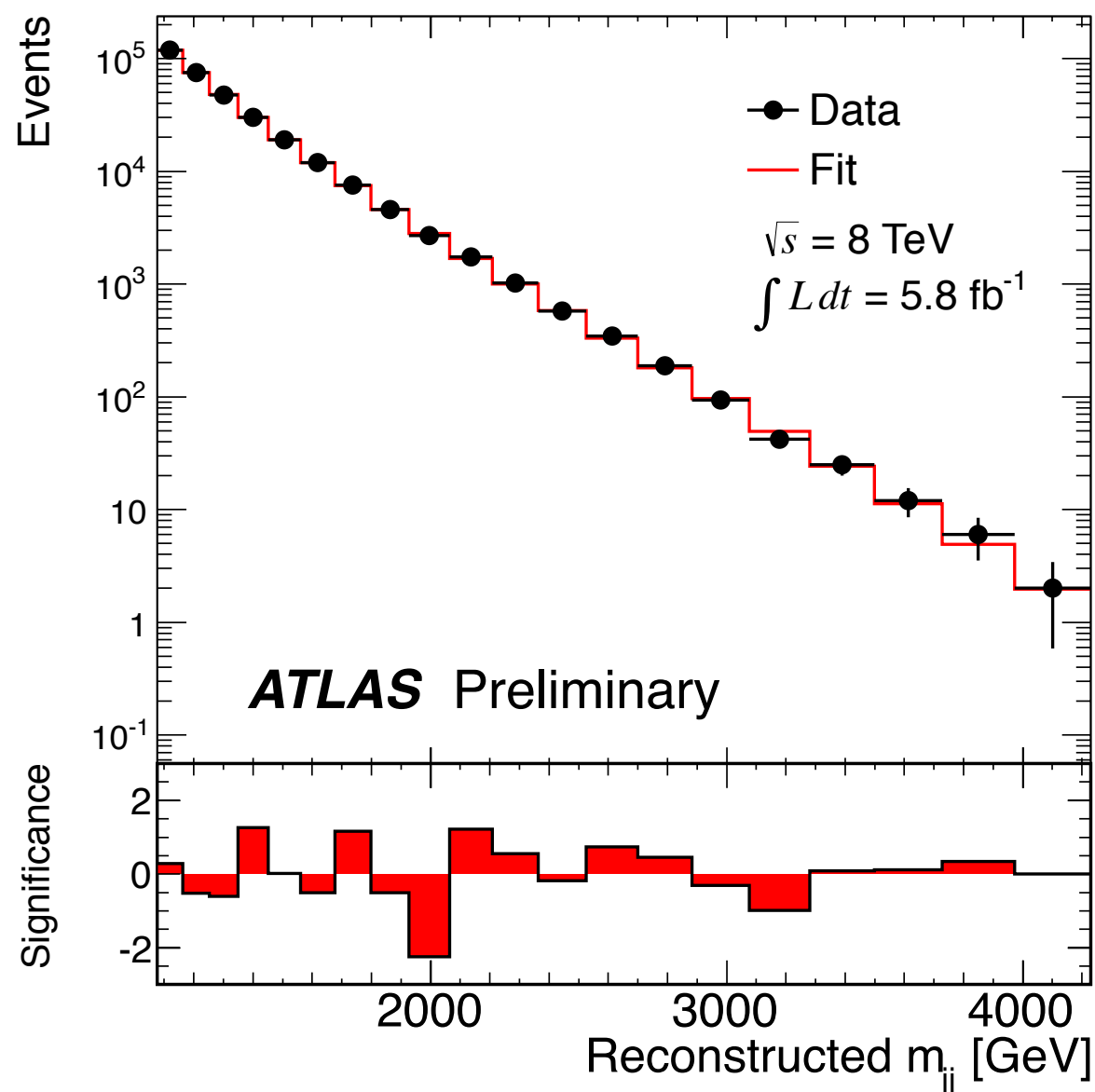
QCD Factorization

$$\sigma_{pp \rightarrow X}(E_{pp}^2) = \int_0^1 dx_1 dx_2 \underbrace{f_i(x_1, \mu^2) f_j(x_2, \mu^2)}_{\substack{\text{parton} \\ \text{distributions} \\ \text{at scale } \mu^2}} \underbrace{\hat{\sigma}_{ij \rightarrow X}(x_1 x_2 E_{pp}^2, \mu^2)}_{\substack{\text{hard process} \\ \text{cross section}}}$$

momentum fractions

- Jet formation and underlying event take place over a much longer time scale, with unit probability
- Hence they cannot affect the cross section
- Scale dependences of parton distributions and hard process cross section are perturbatively calculable, and cancel order by order

Dijet Mass Distribution



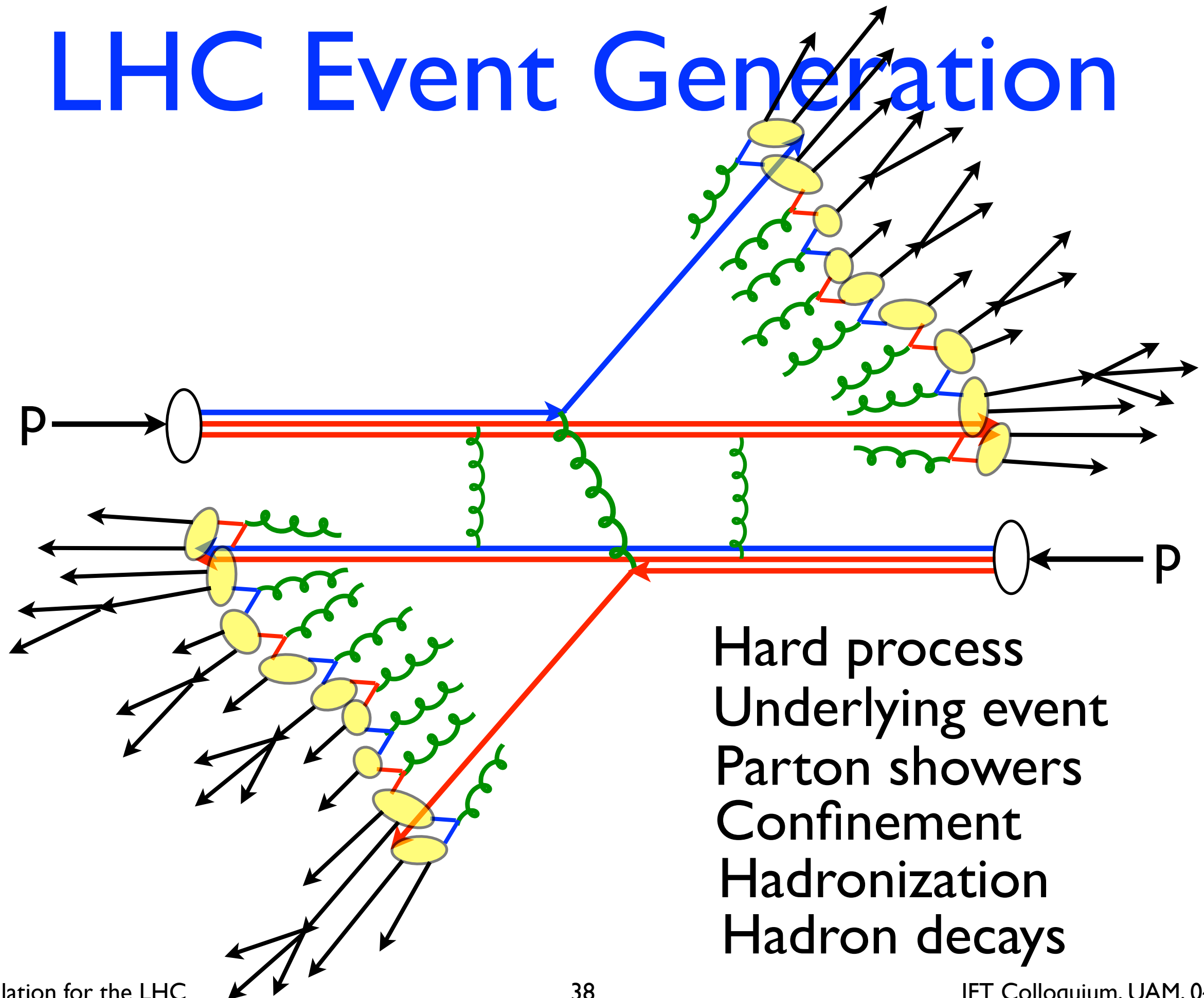
- $5.8 \text{ fb}^{-1} = 5.8 \text{ events per fb}$
- $1 \text{ fb} = 10^{-15} \text{ barn}$ ($1 \text{ barn} = 10^{-28} \text{ m}^2 \sim \text{nuclear size}$)
- No sign of deviation from Standard Model (yet)

Monte Carlo Event Generation

Monte Carlo Event Generation

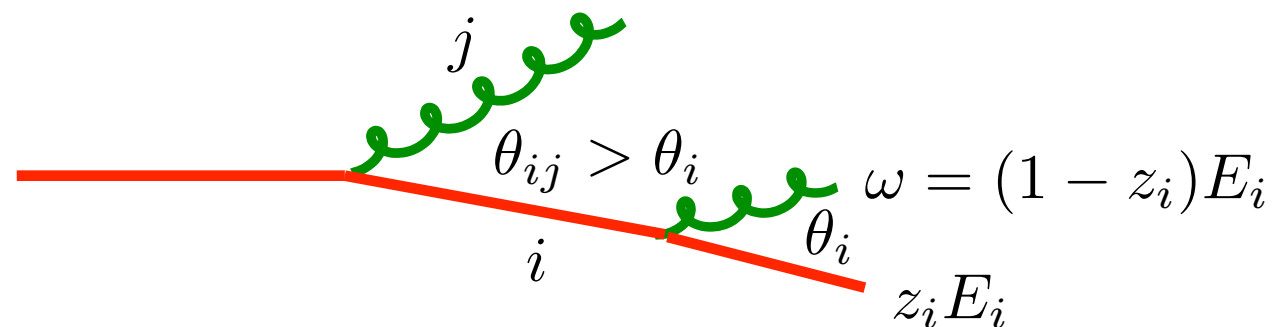
- Aim is to produce simulated (particle-level) datasets like those from real collider events
 - ✧ i.e. lists of particle identities, momenta, ...
 - ✧ simulate quantum effects by (pseudo)random numbers
- Essential for:
 - ✧ Designing new experiments and data analyses
 - ✧ Correcting for detector and selection effects
 - ✧ Testing the SM and measuring its parameters
 - ✧ Estimating new signals and their backgrounds

LHC Event Generation



Parton Shower Approximation

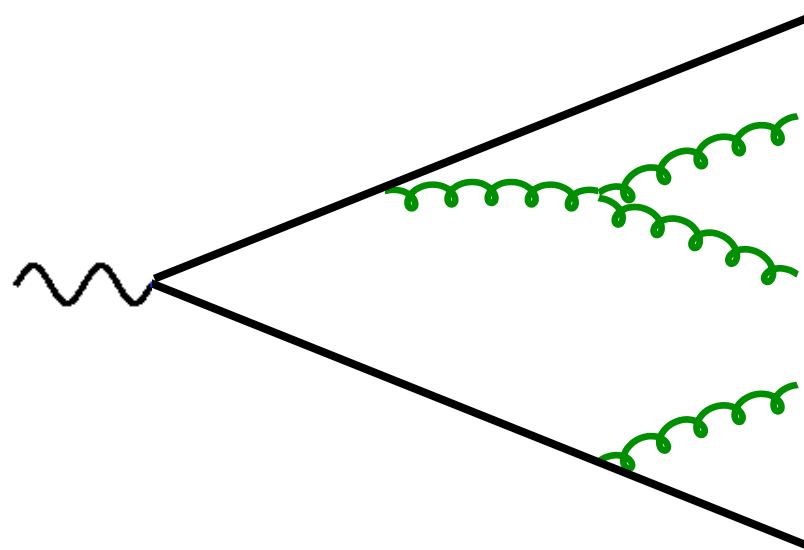
- Keep only most singular parts of QCD matrix elements:
- **Collinear** $d\sigma_{n+1} \approx \frac{\alpha_S}{2\pi} \sum_i P_{ii}(z_i, \phi_i) dz_i \frac{d\xi_i}{\xi_i} \frac{d\phi_i}{2\pi} d\sigma_n$ $\xi_i = 1 - \cos \theta_i$
- **Soft** $d\sigma_{n+1} \approx \frac{\alpha_S}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{p_i \cdot p_j}{p_i \cdot k p_j \cdot k} \omega d\omega d\xi_i \frac{d\phi_i}{2\pi} d\sigma_n$
 $= \frac{\alpha_S}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \frac{\xi_{ij}}{\xi_i \xi_j} \frac{d\omega}{\omega} d\xi_i \frac{d\phi_i}{2\pi} d\sigma_n$
 $\approx \frac{\alpha_S}{2\pi} \sum_{i,j} (-\mathbf{T}_i \cdot \mathbf{T}_j) \Theta(\xi_{ij} - \xi_i) \frac{d\omega}{\omega} \frac{d\xi_i}{\xi_i} d\sigma_n$



➔ Angular-ordered **parton shower**

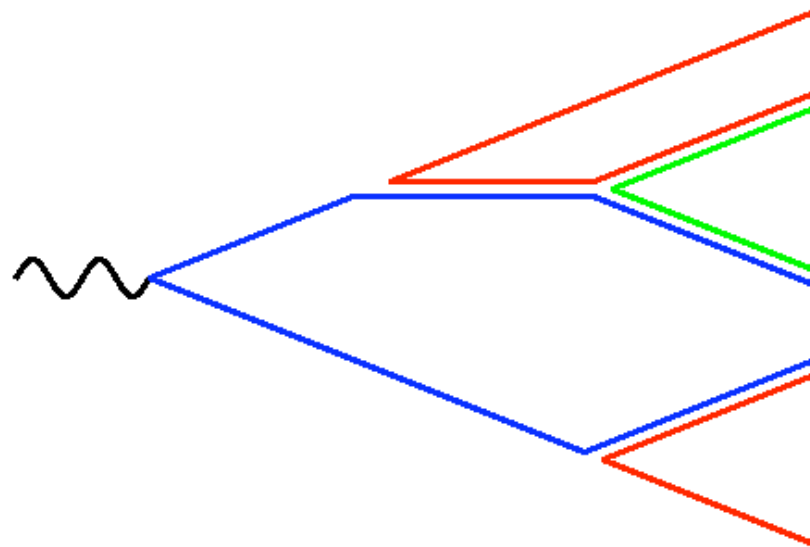
Cluster Hadronization Model

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near $\Lambda_{\text{QCD}} \sim 200$ MeV, perturbation theory breaks down and hadrons are formed
- Before that, at scales $Q_0 \sim \text{few} \times \Lambda_{\text{QCD}}$, there is universal **preconfinement** of colour
- Decay of preconfinement clusters provides a basis for hadronization models



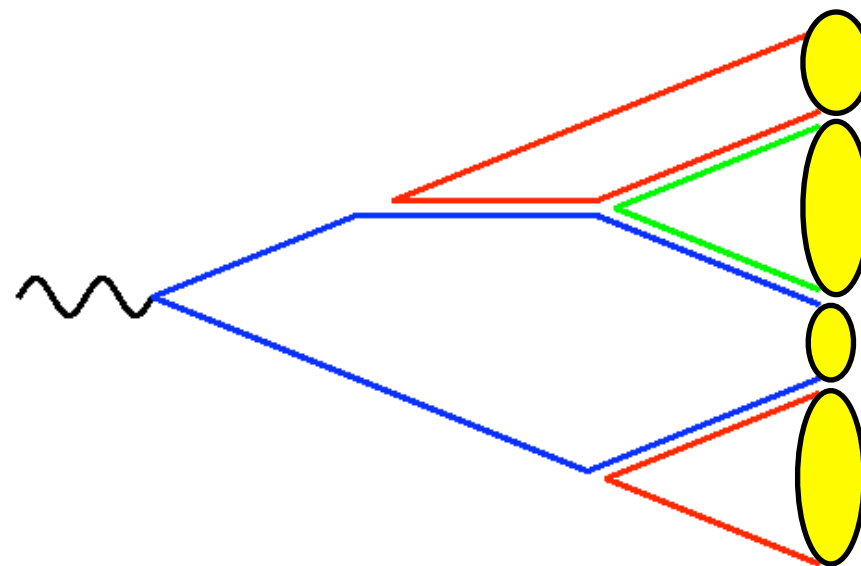
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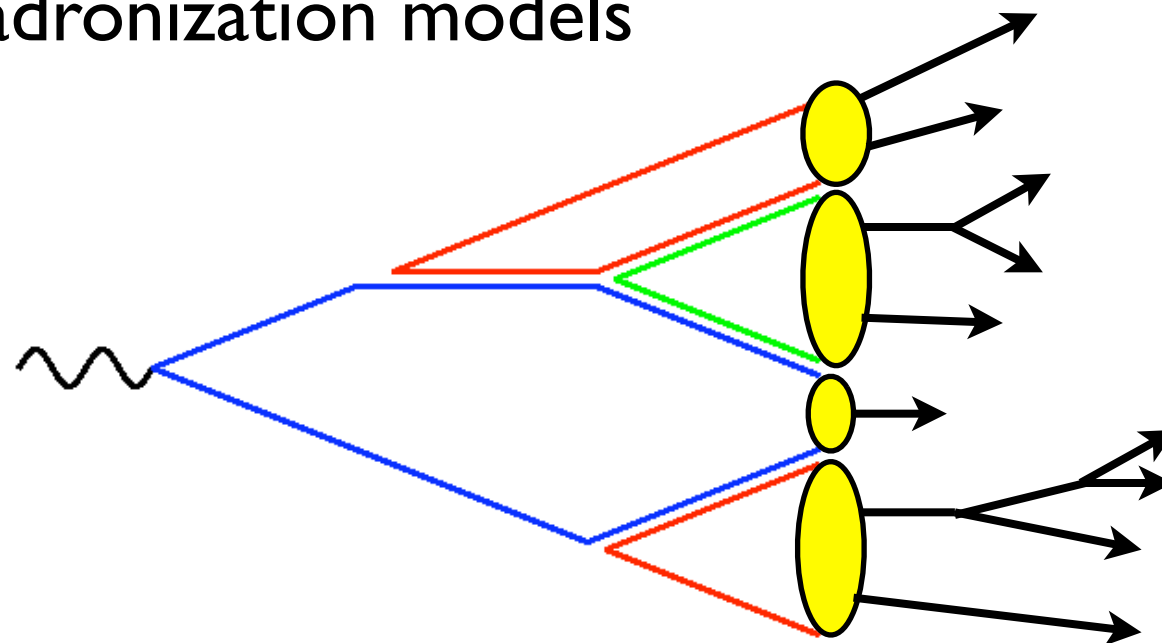
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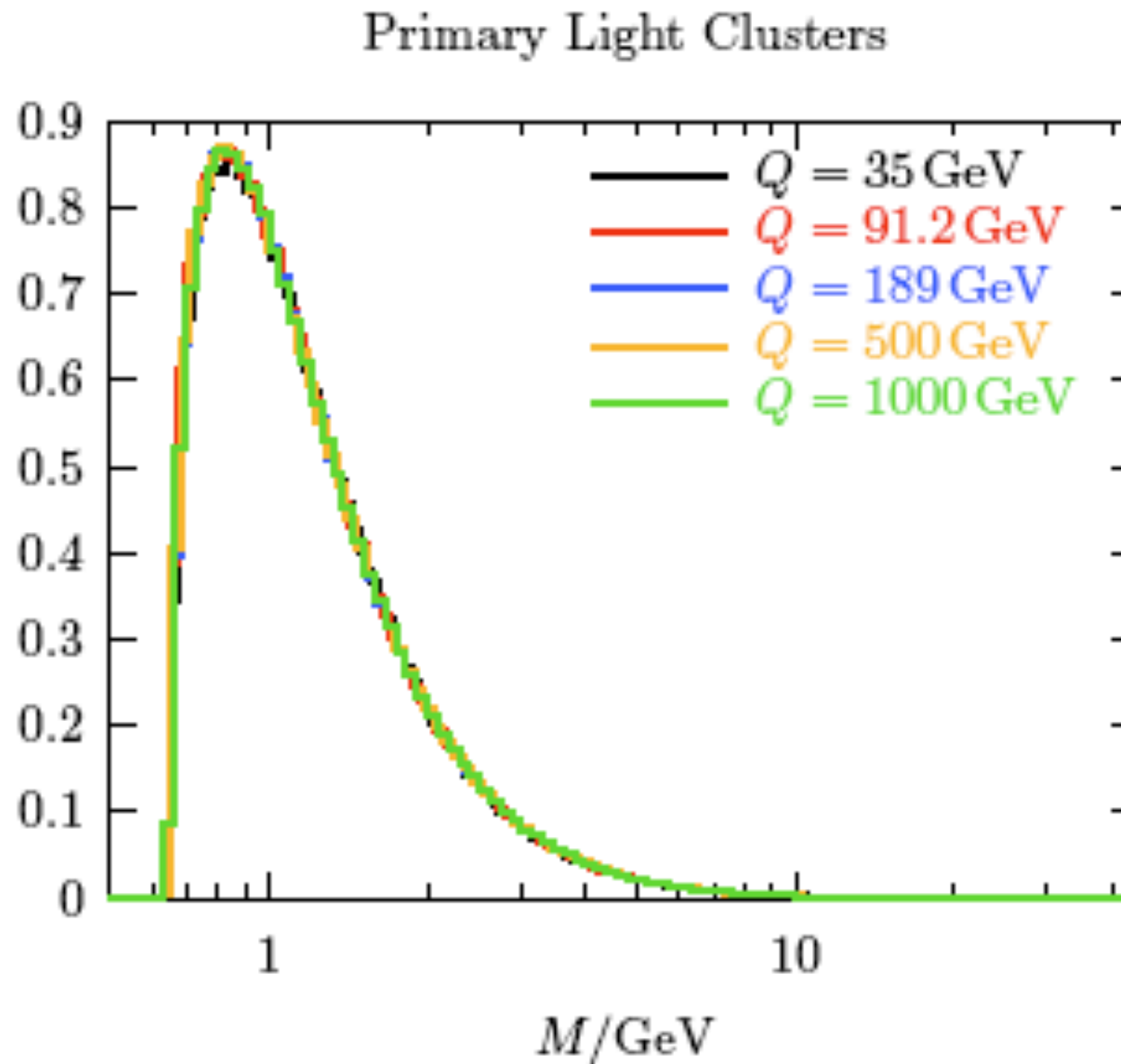


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- Decay of preconfinement clusters provides a basis for hadronization models



Colour Preconfinement



- Mass distribution of preconfinement clusters is universal

Monte Carlo Event Generators

- Traditionally (imprecise) general-purpose tools



- Much recent work to make them more precise

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/>

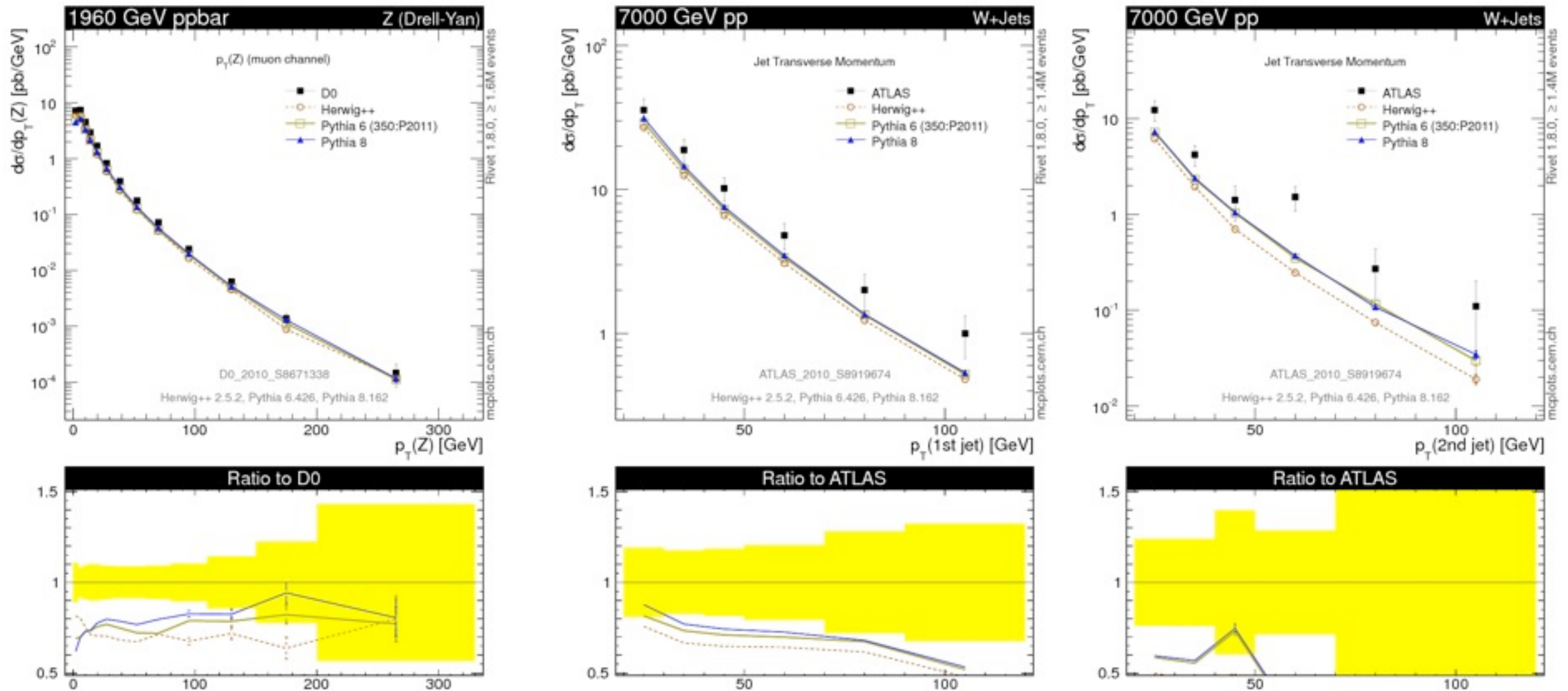
- ➔ Dipole-type parton shower, cluster hadronization
- ➔ C++

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

Parton Shower Monte Carlo

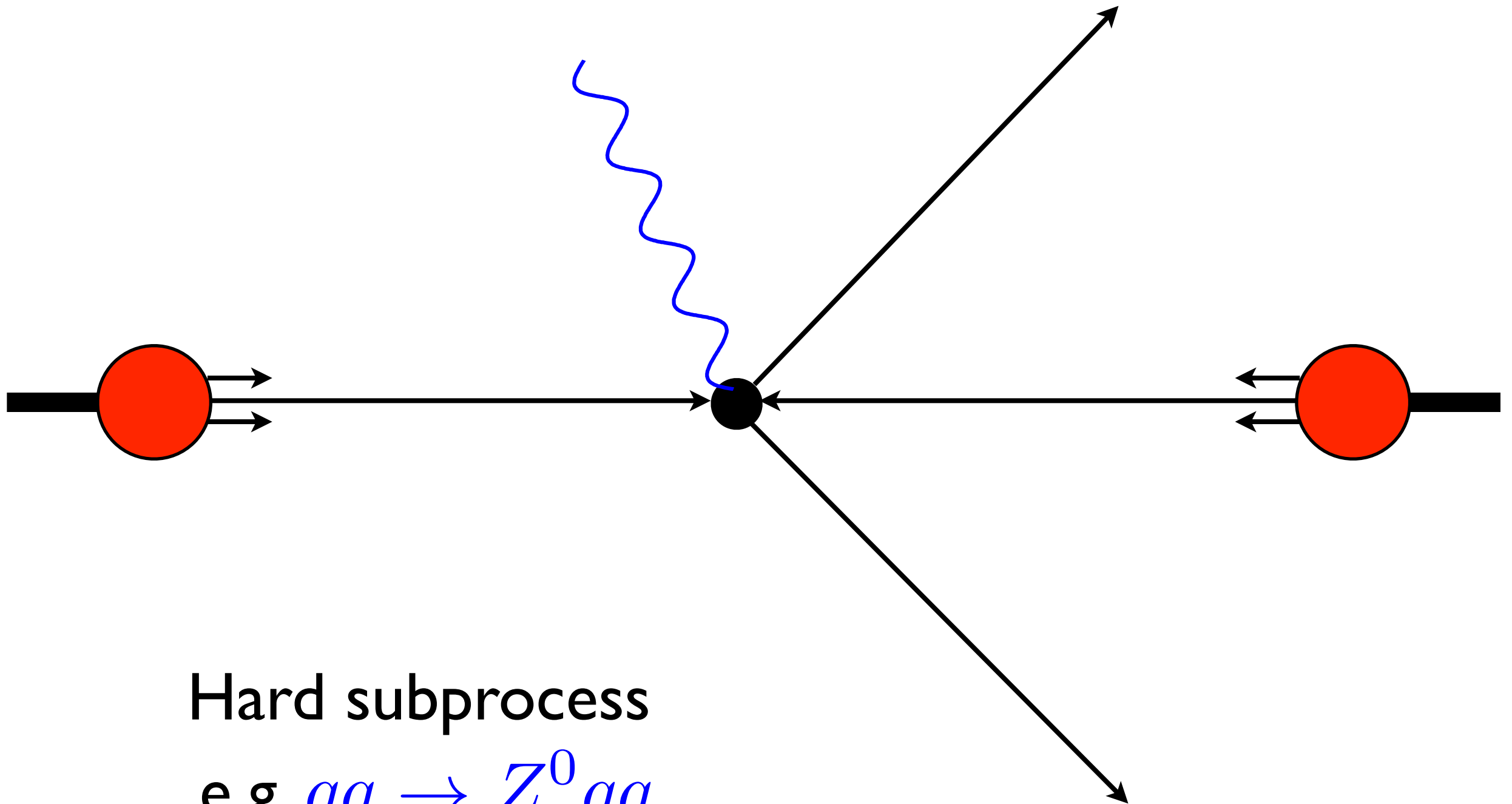
<http://mcplots.cern.ch/>

- Hard subprocess: $q\bar{q} \rightarrow Z^0/W^\pm$



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

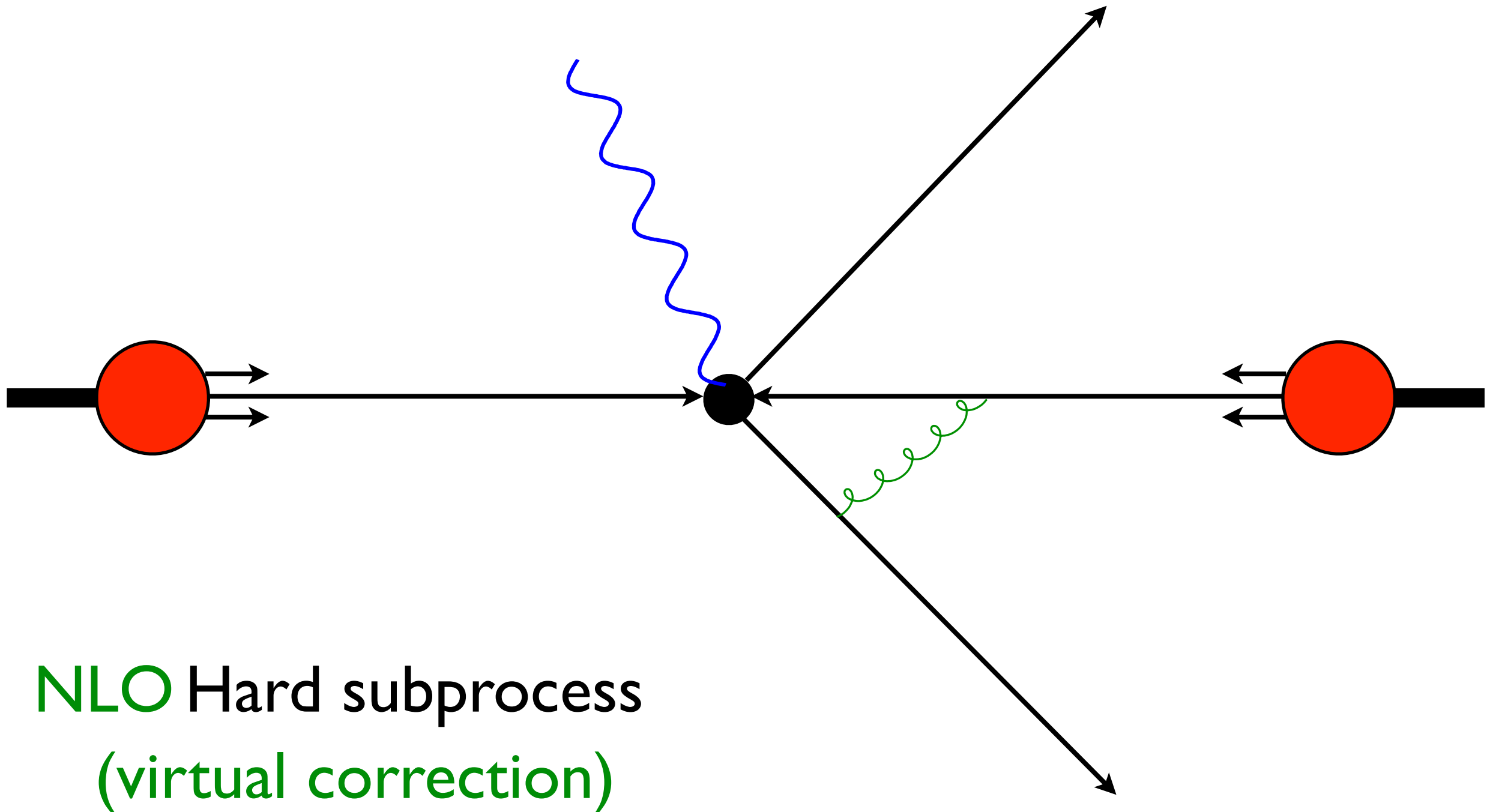
Improving Event Simulation



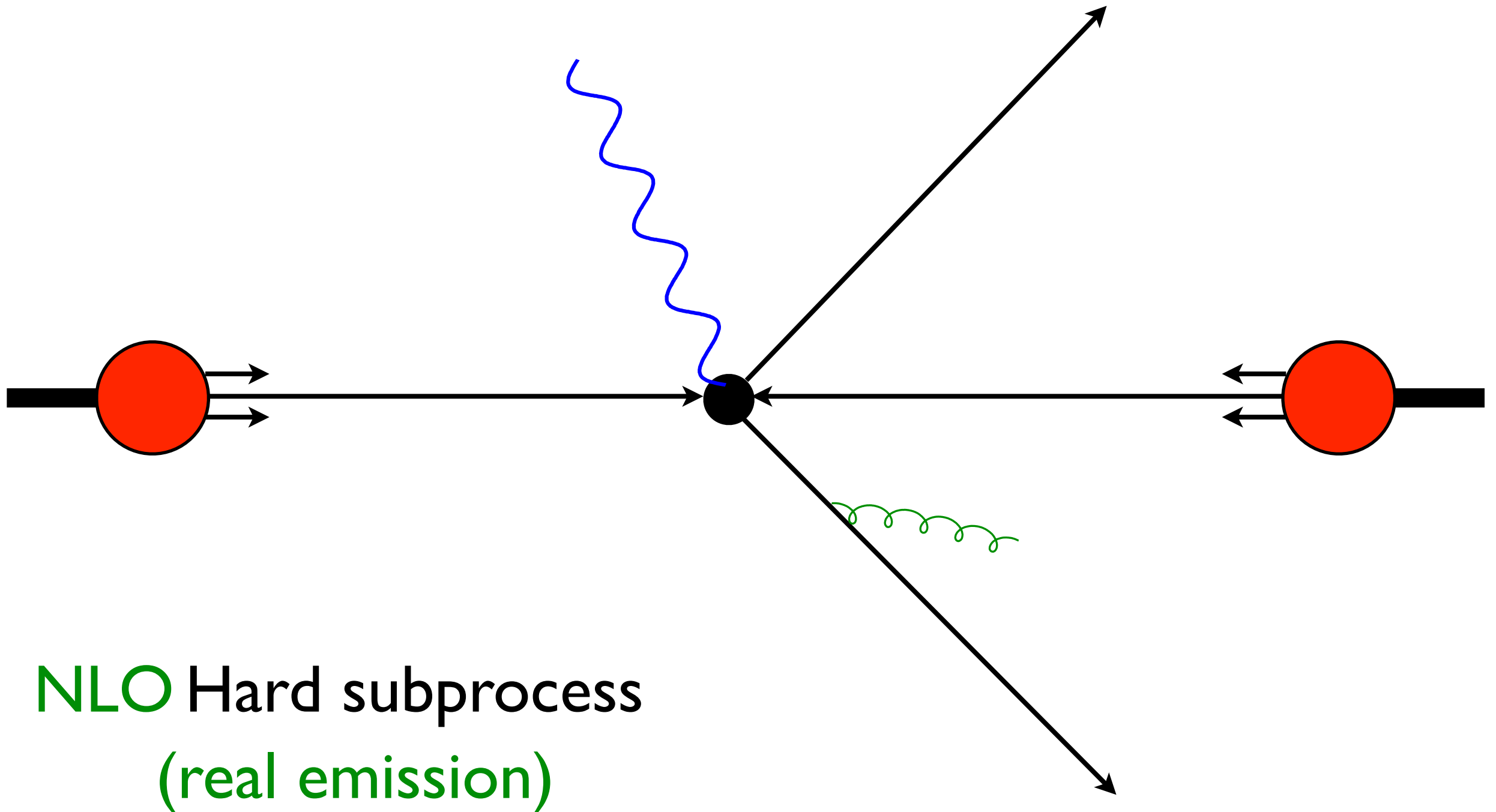
Hard subprocess

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

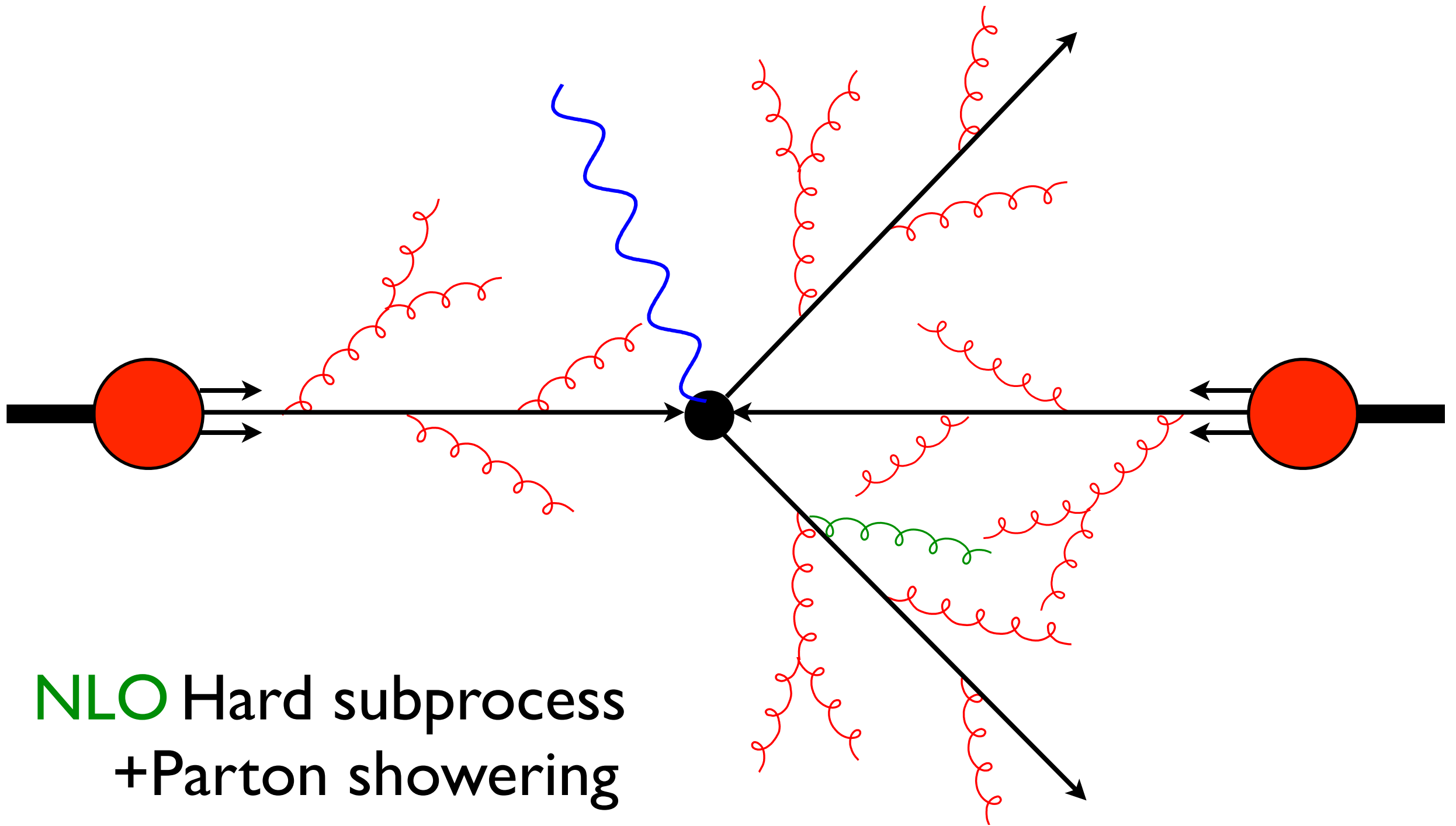
Improving Event Simulation



Improving Event Simulation

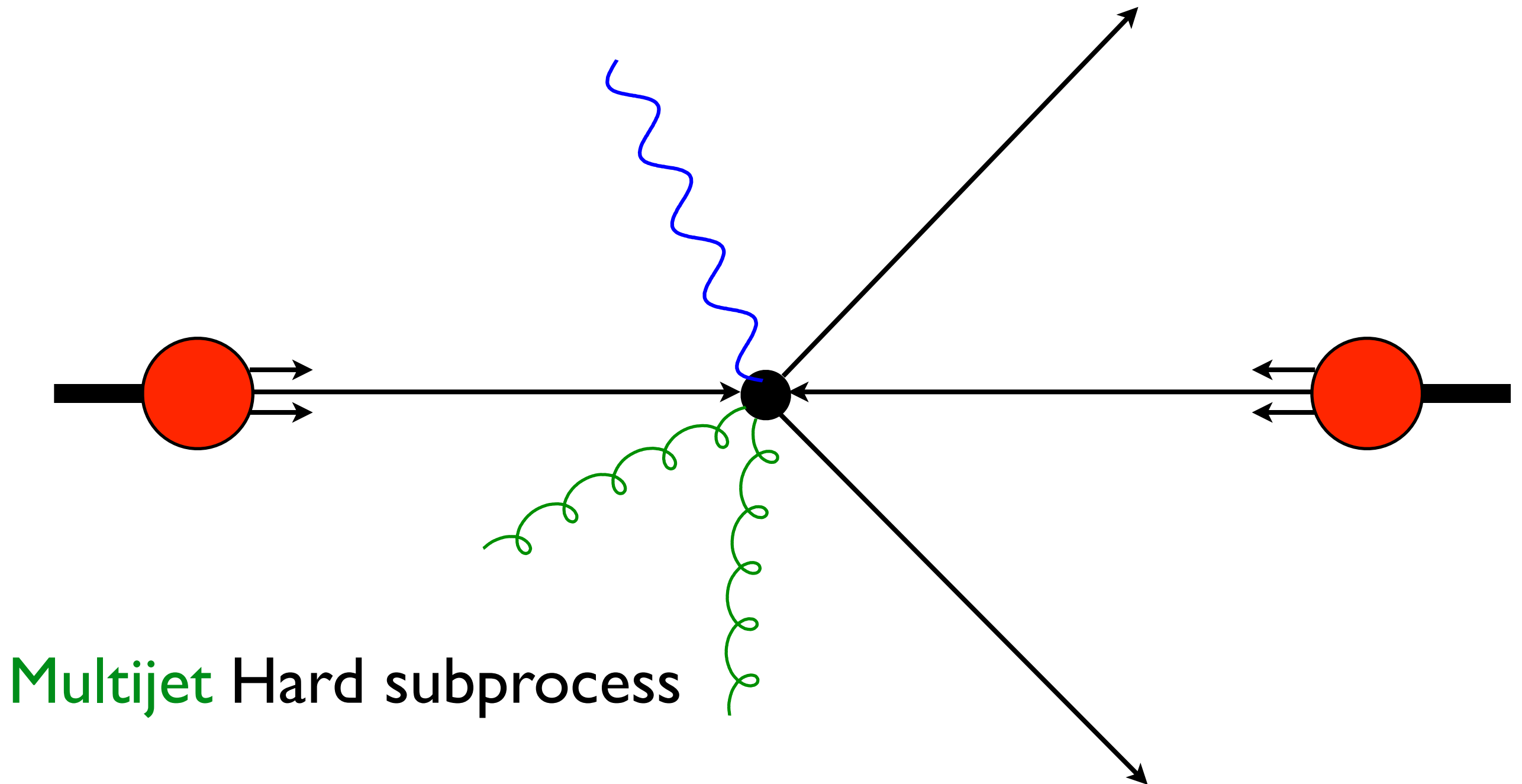


Improving Event Simulation

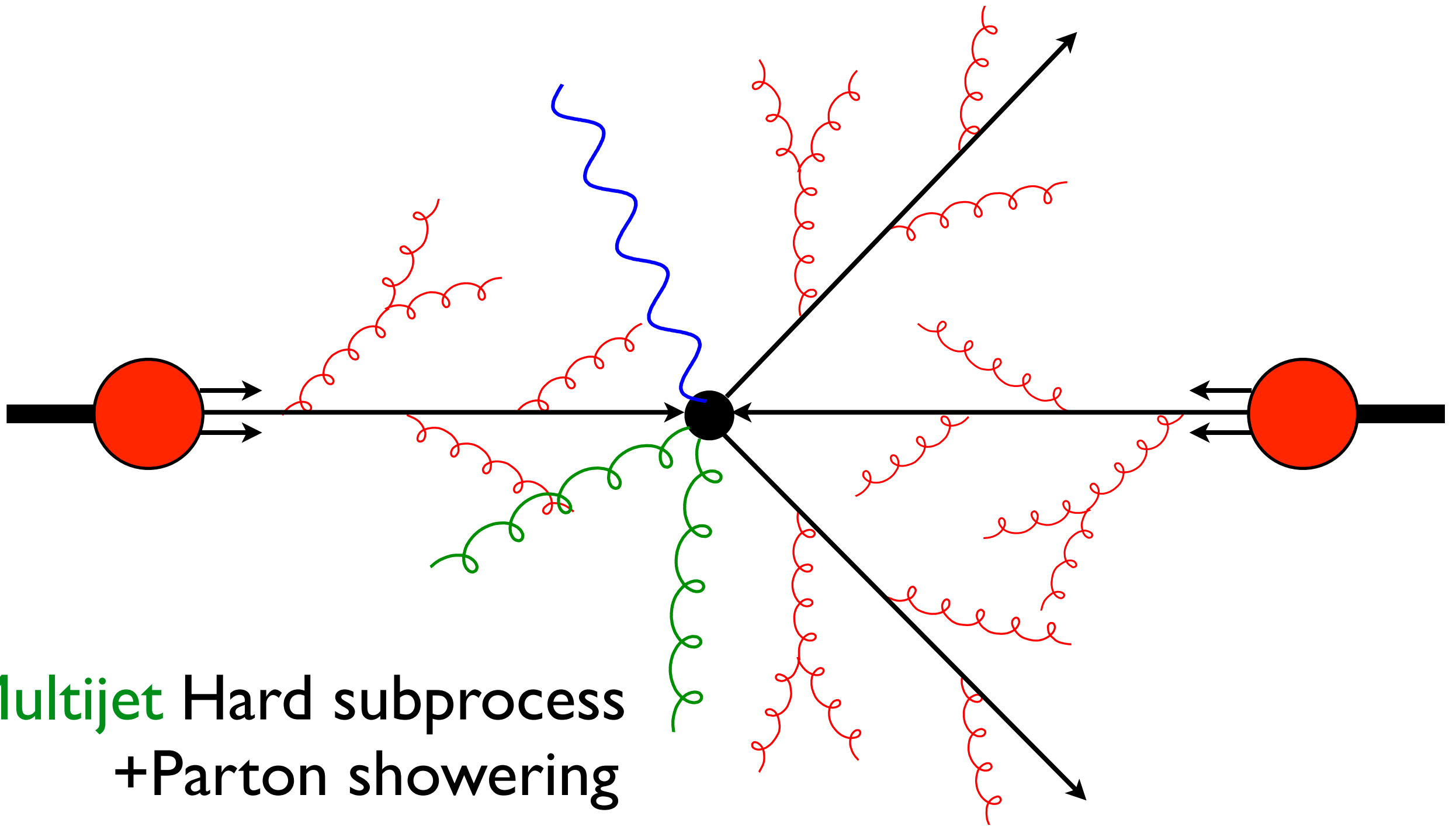


NLO Hard subprocess
+Parton showering
= Double counting??

Improving Event Simulation



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

S Frixione & BW, JHEP 06(2002)029

- Compute parton shower contributions (real and virtual) at NLO
 - ✧ Generator-dependent
- Subtract these from exact NLO
 - ✧ Cancels divergences of exact NLO!
- Generate modified no-emission (LO+virtual) and real-emission hard process configurations
 - ✧ Some may have negative weight
- Pass these through parton shower etc.
 - ✧ Only shower-generated terms beyond NLO

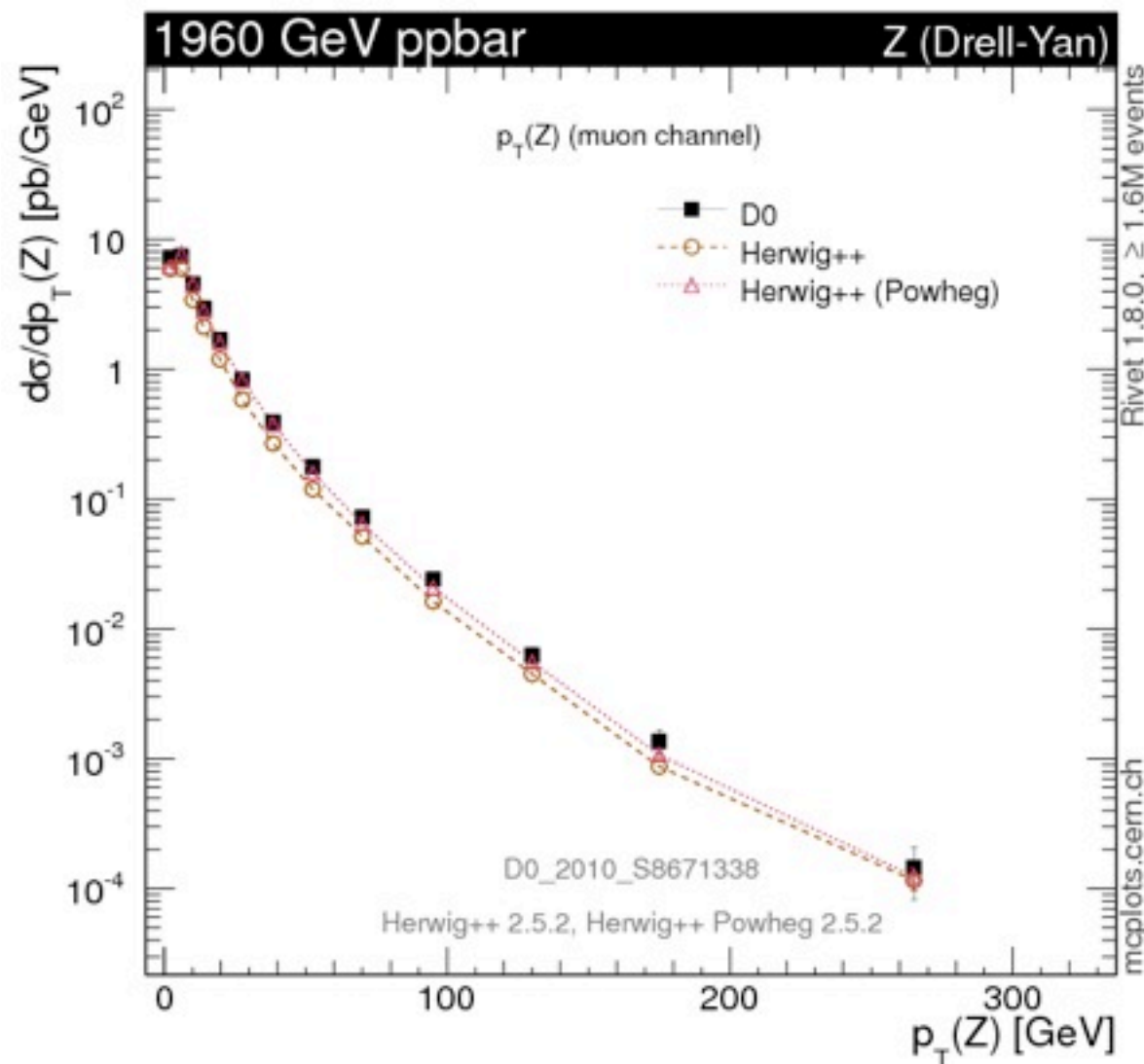
POWHEG matching

P Nason, JHEP 11(2004)040

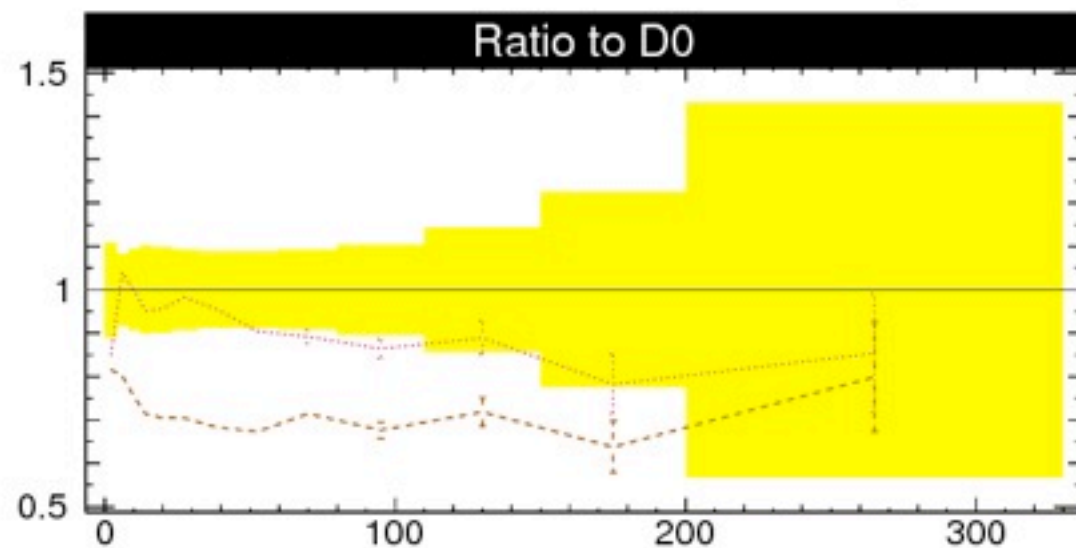
- POsitive Weight Hardest Emission Generator
- Use exact real-emission matrix element to generate hardest (highest relative p_T) emission configurations
 - ✧ No-emission probability implicitly modified
 - ✧ (Almost) eliminates negative weights
 - ✧ Some uncontrolled terms generated beyond NLO
- Pass configurations through parton shower etc

Z^0 at Tevatron

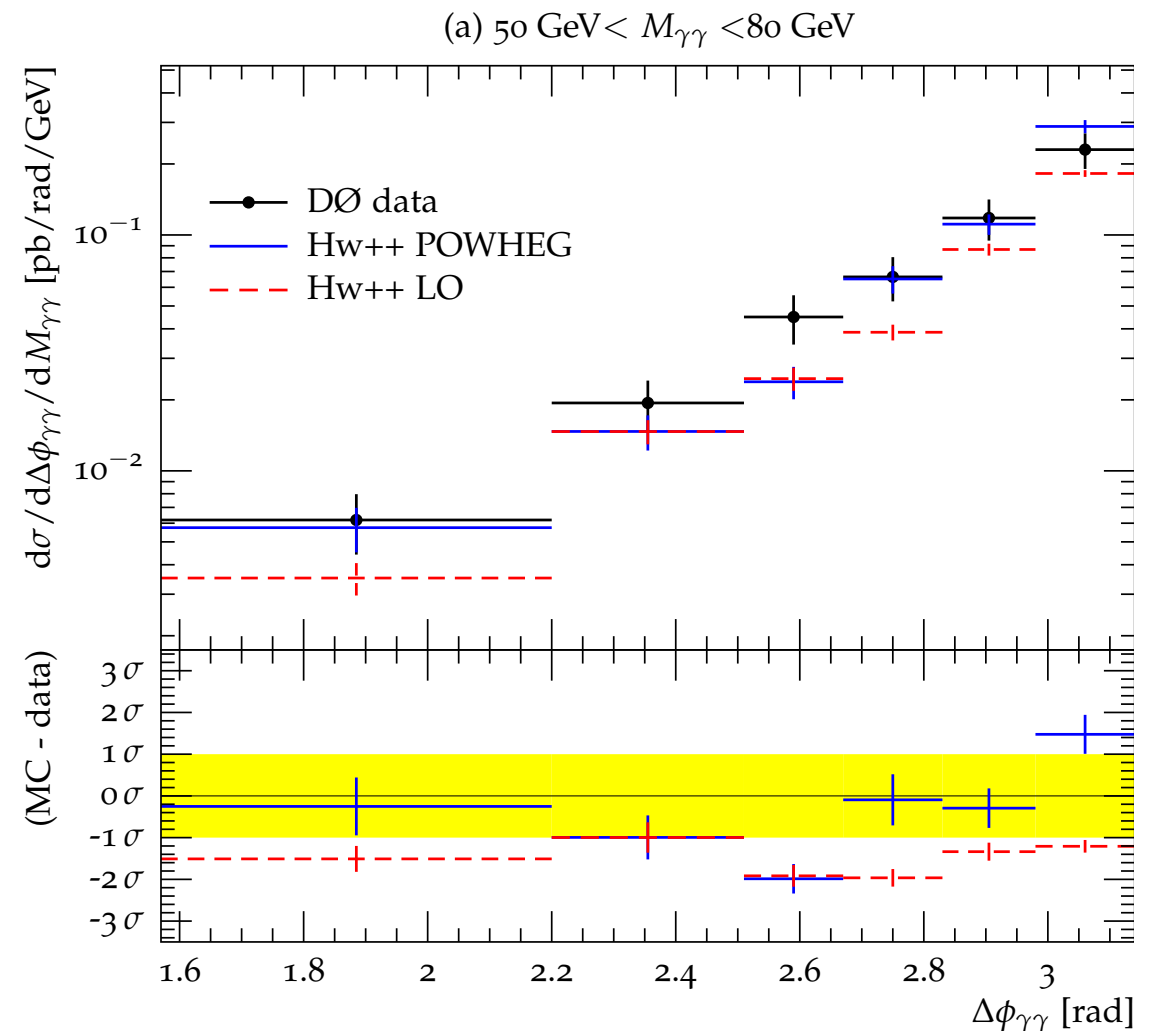
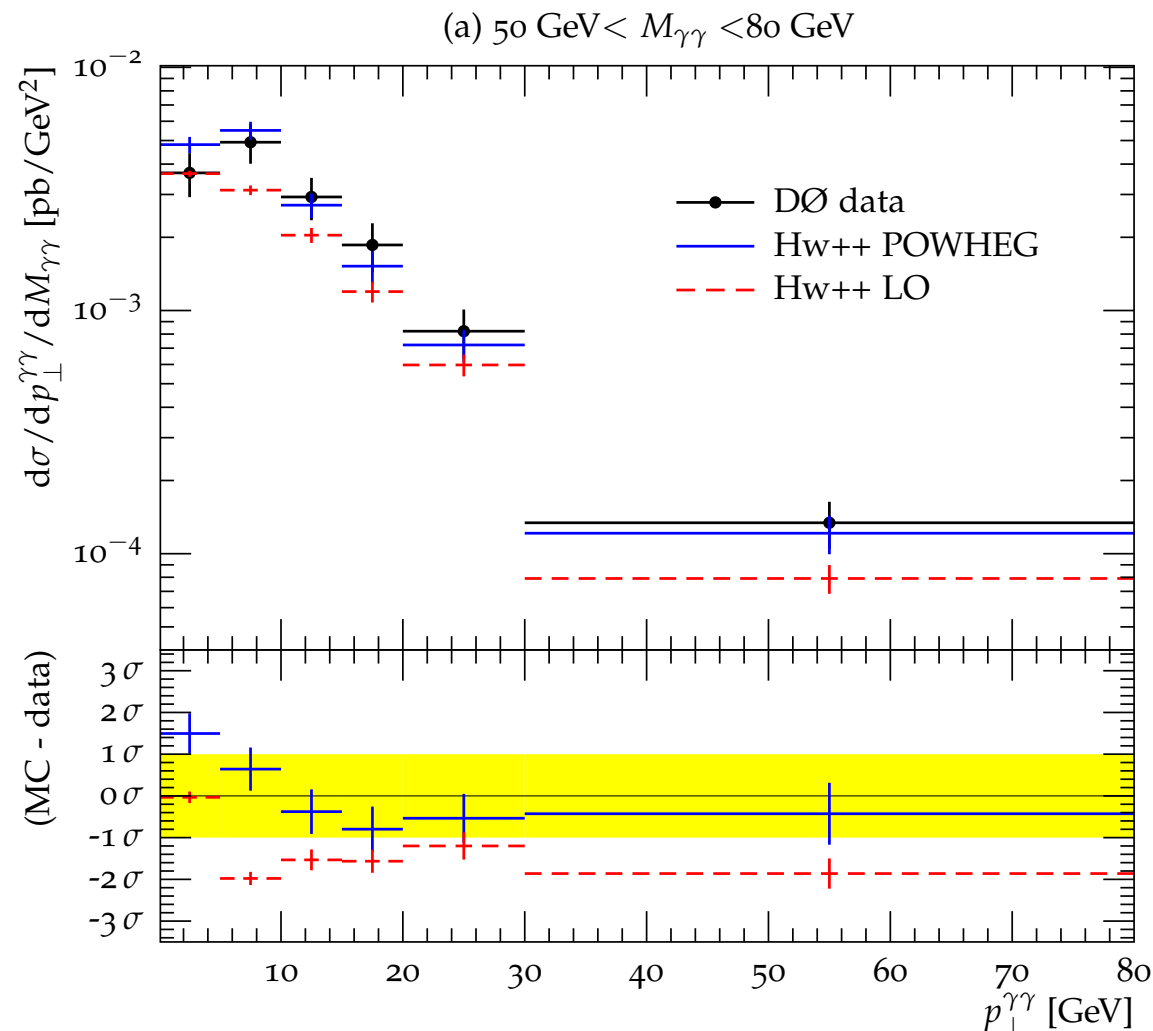
<http://mcplots.cern.ch/>



- Absolute normalization: LO too low
- POWHEG agrees with rate and distribution



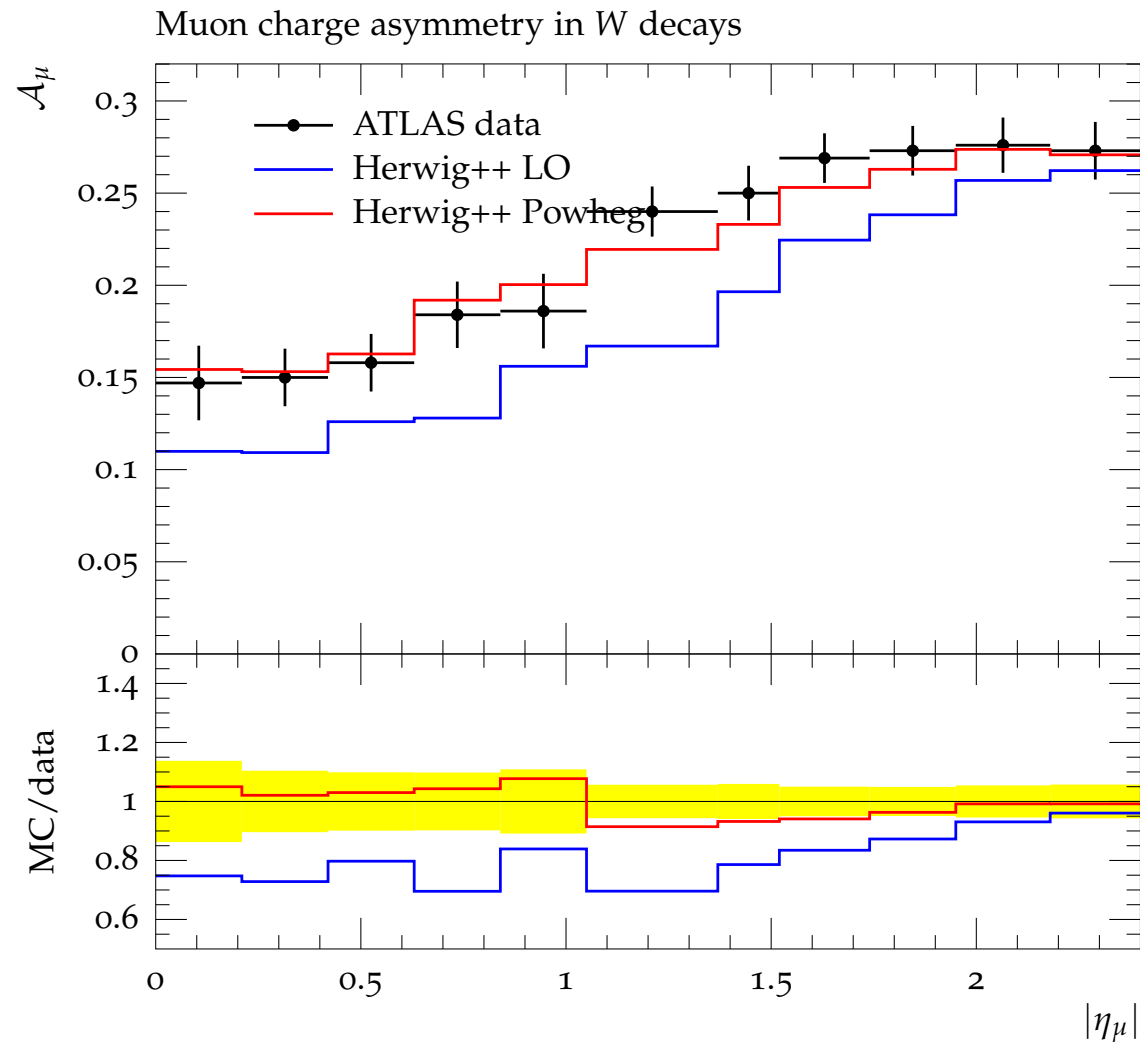
$\gamma\gamma$ at Tevatron



- Absolute normalization → LO too low
- POWHEG agrees with rate and distribution
- At LHC, important background for Higgs search

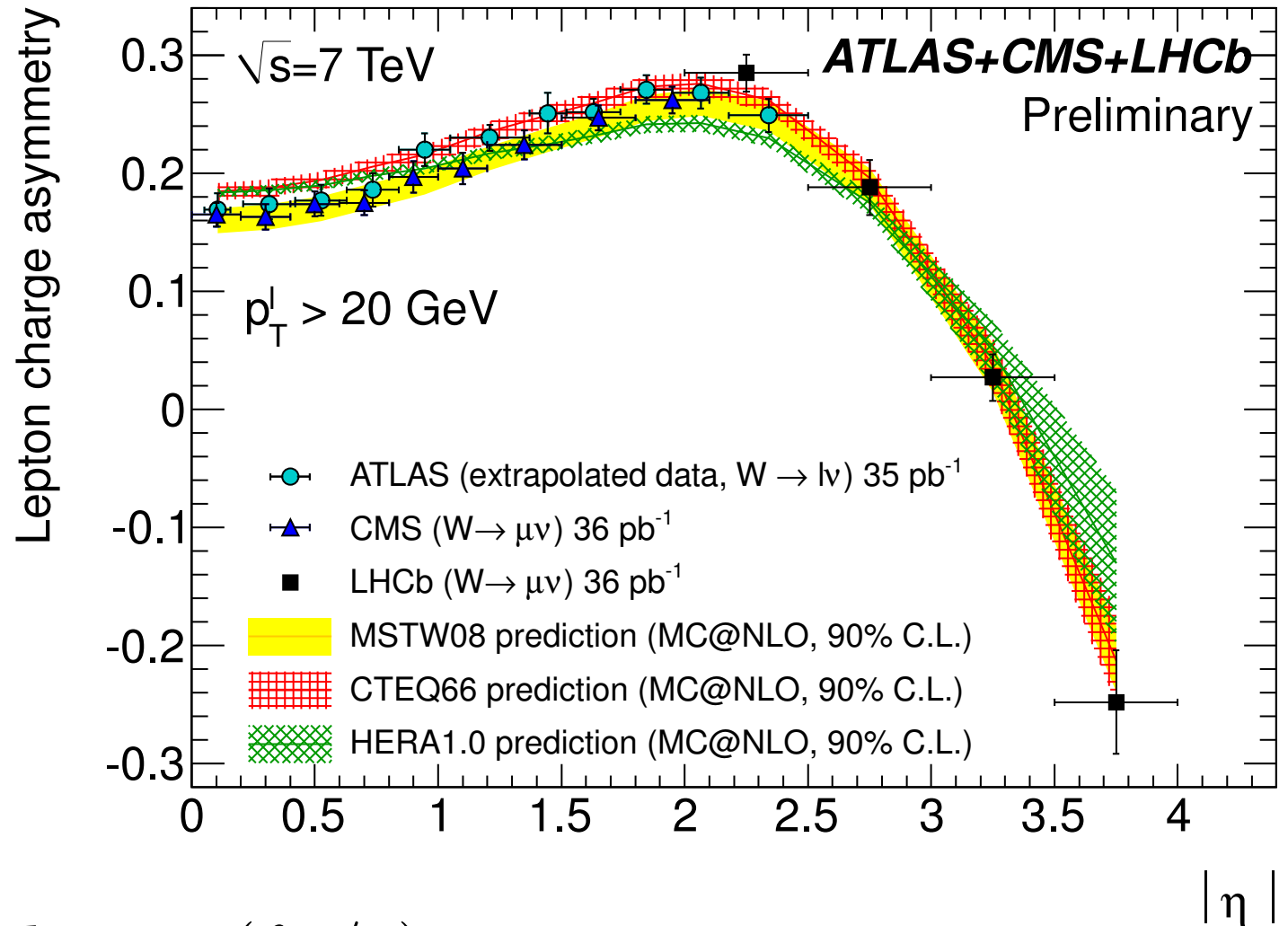
D'Errico & Richardson, JHEP02(2012)130

W asymmetry at LHC



$$A_\mu = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$$

$$\eta_\mu = \log \tan(\theta_\mu/2)$$



ATLAS-CONF-1211-129

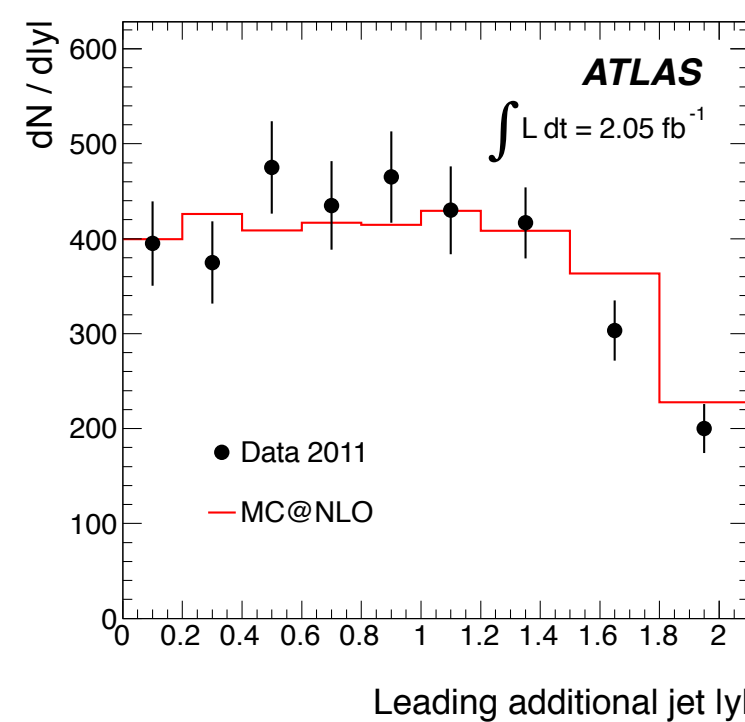
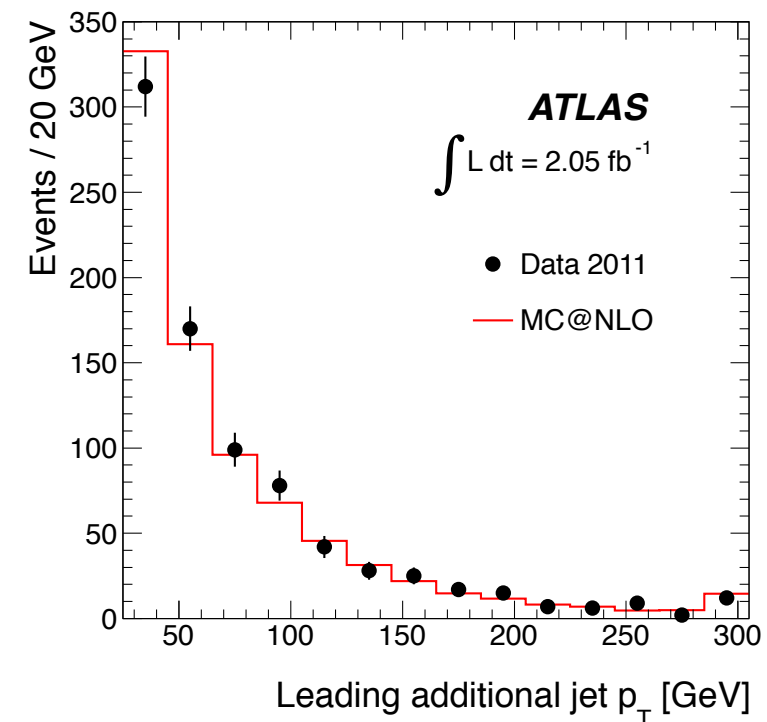
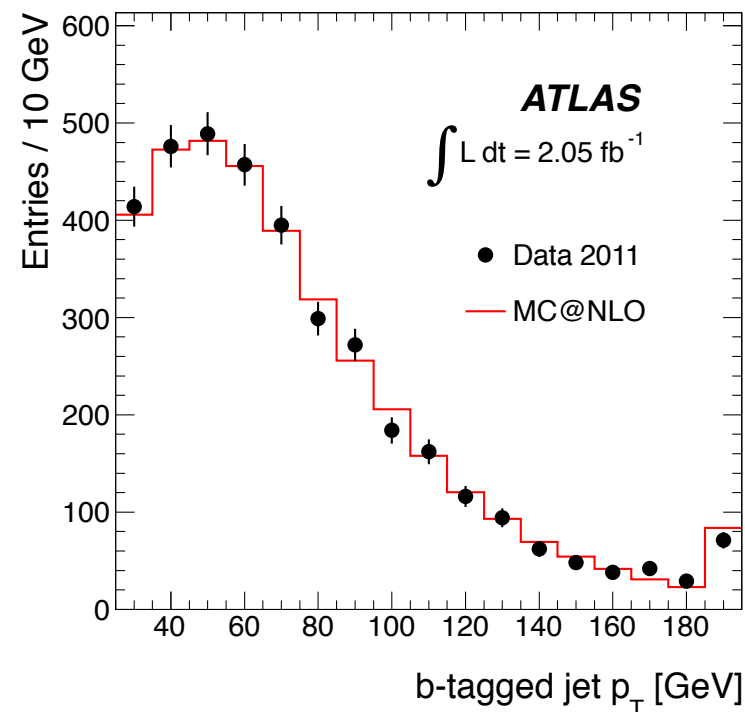
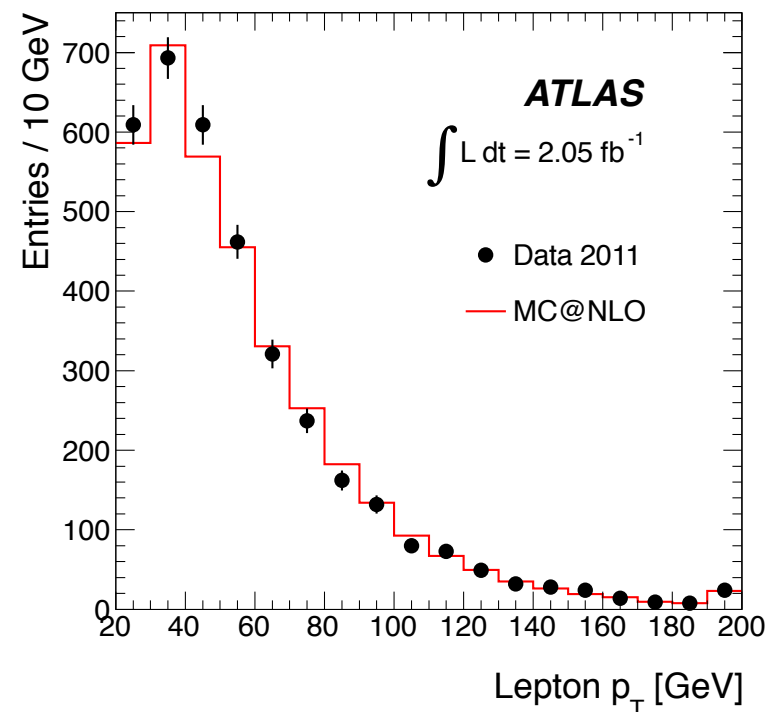
- Asymmetry probes parton distributions

$$u\bar{d} \rightarrow W^+ \rightarrow \mu^+ \nu_\mu \quad \text{vs} \quad d\bar{u} \rightarrow W^- \rightarrow \mu^- \bar{\nu}_\mu$$

Top quark at LHC

- Top pair production
- ATLAS at LHC (7 TeV)
- Rapidity $y = \frac{1}{2} \log \left(\frac{E + p_L}{E - p_L} \right)$
- Both decays leptonic:

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

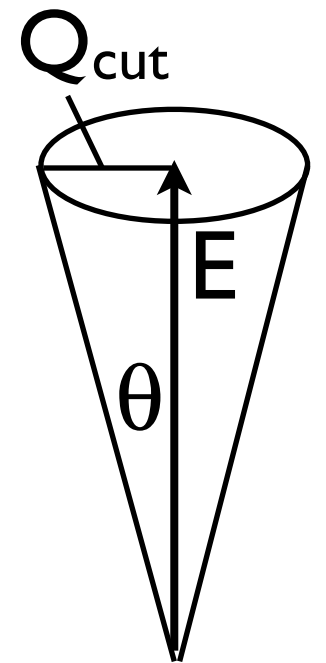


ATLAS, arXiv:1203.5015

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

Multijet Merging

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



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

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

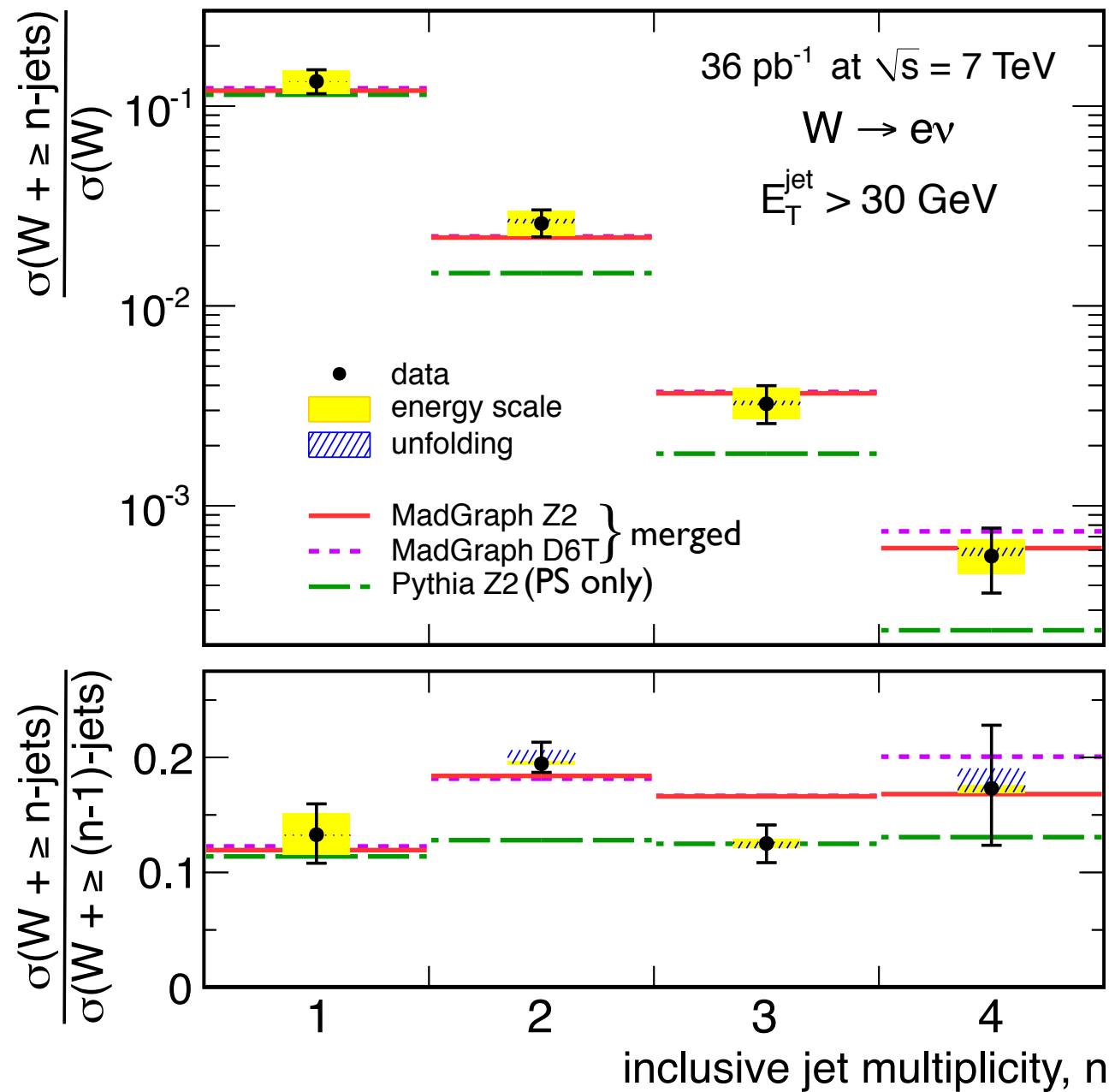
-L: Lonnblad, JHEP 05(2002)063

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

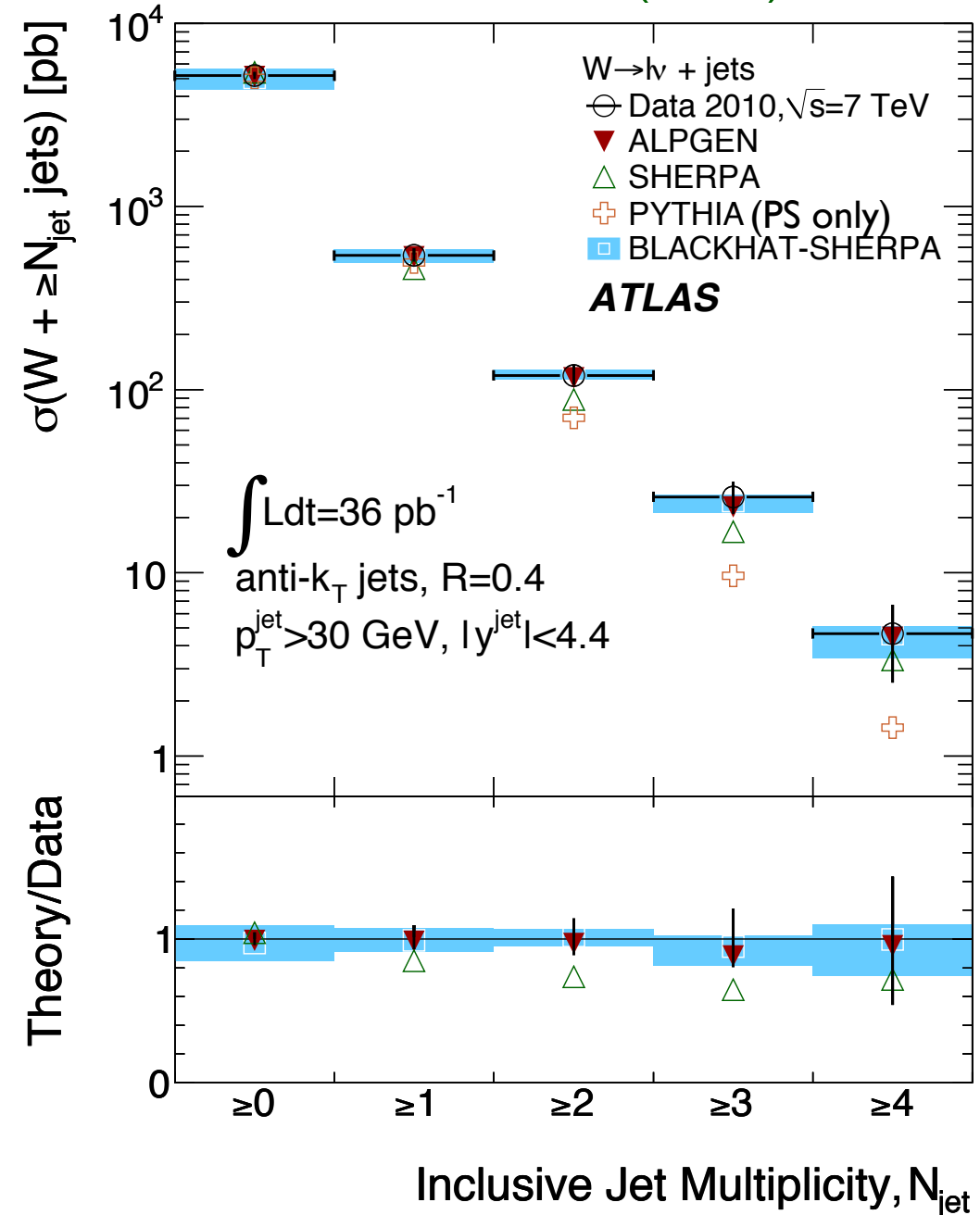
W+jets at LHC

CMS, JHEP01(2012)010

CMS

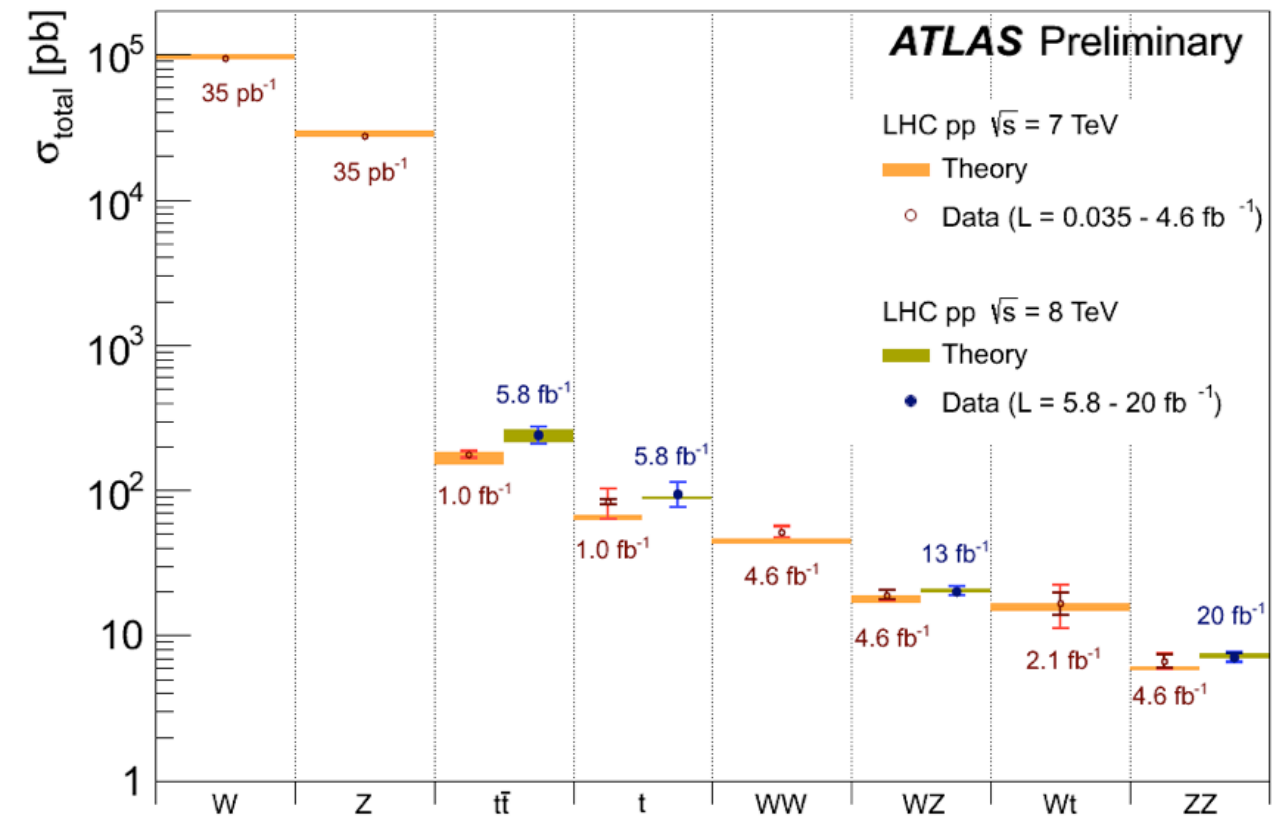
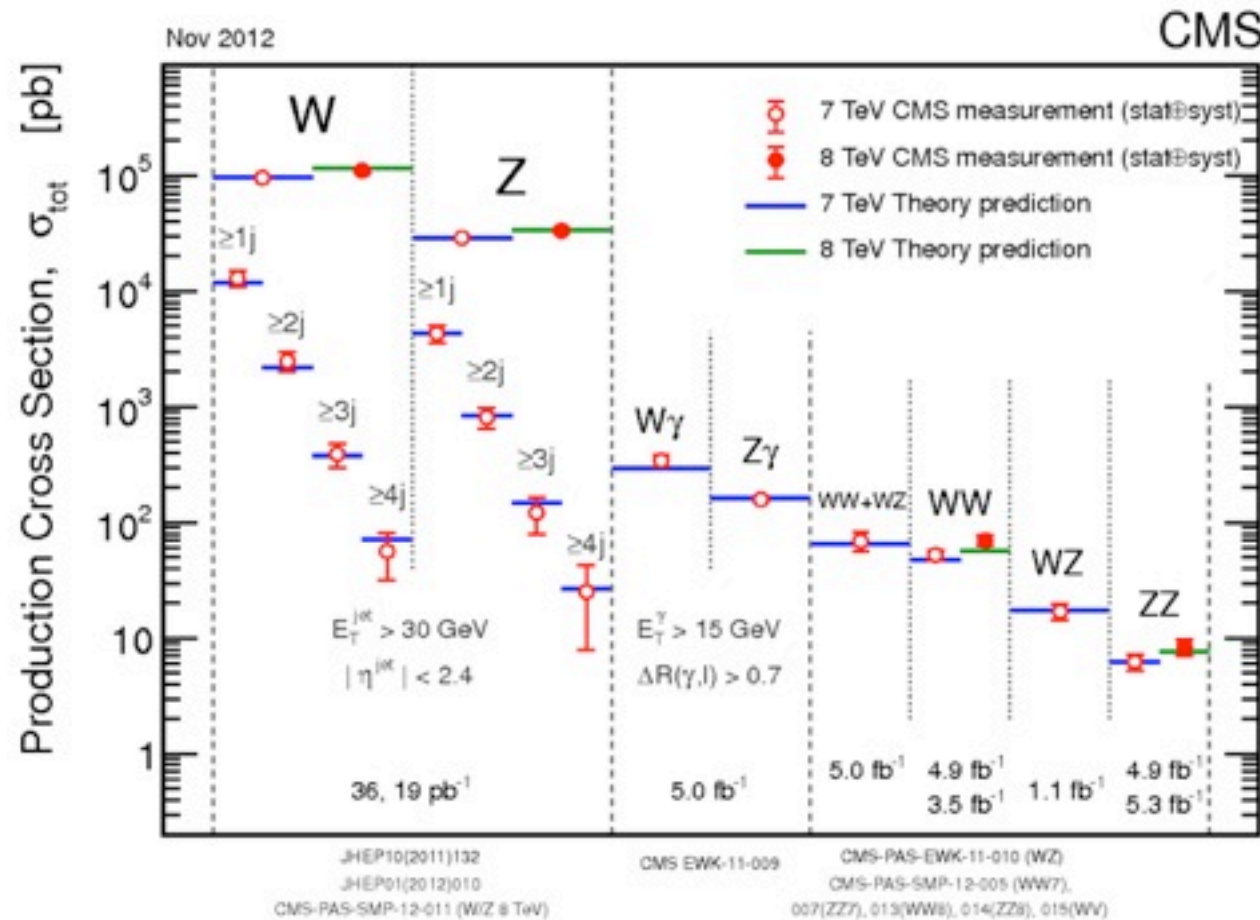


ATLAS, PRD85(2012)092002



- Very good agreement with predictions from merged simulations, while parton shower alone starts to fail for $n_{\text{jet}} \geq 2$

LHC Cross Section Summary

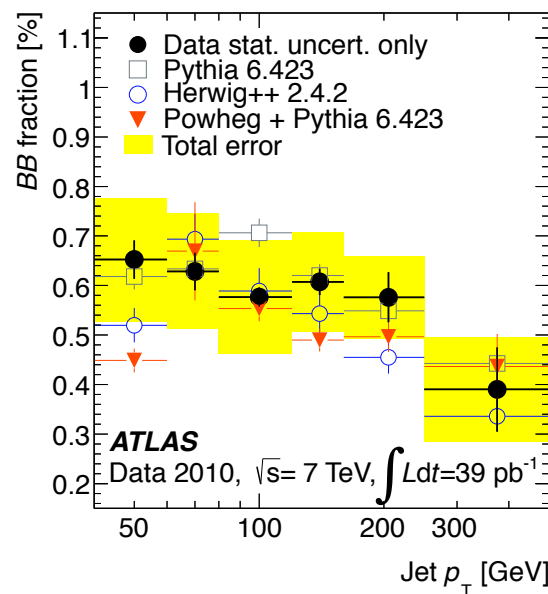


- Surprisingly good agreement
- No sign of non-Standard-Model phenomena (yet)

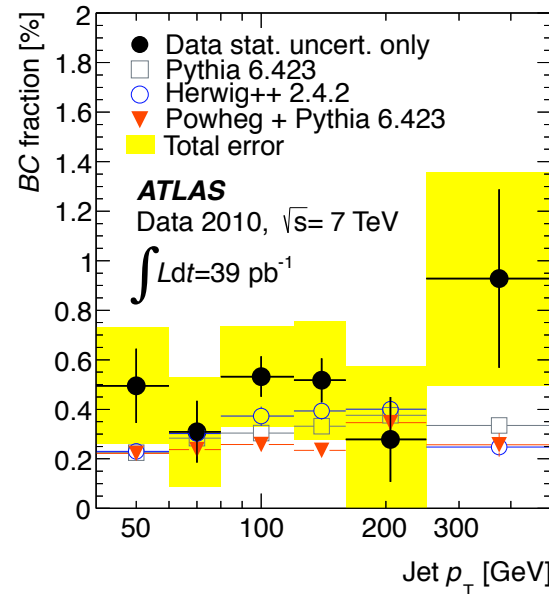
But all is not perfect ...

- Dijet flavours versus jet p_T

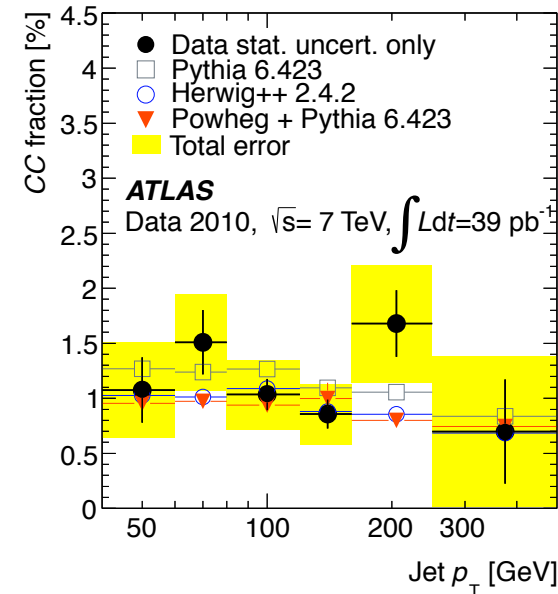
ATLAS, arXiv:1210.0441



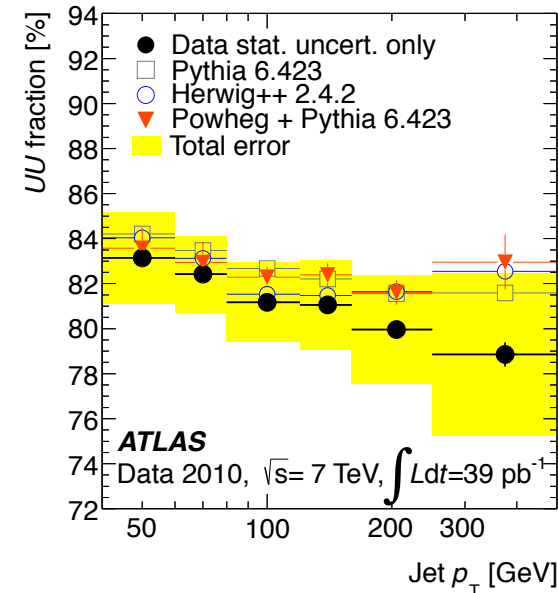
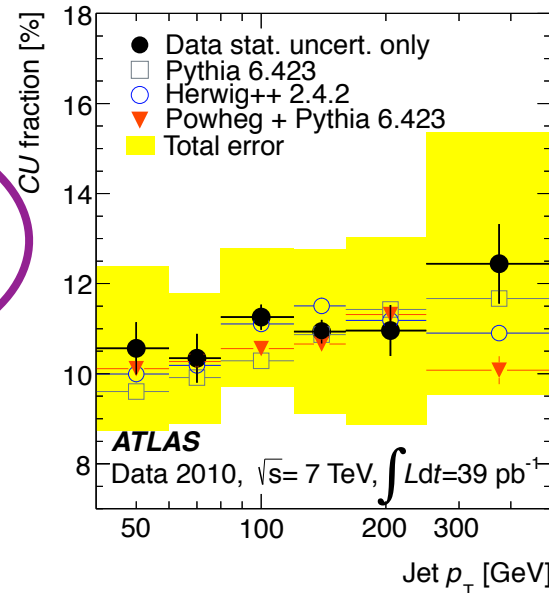
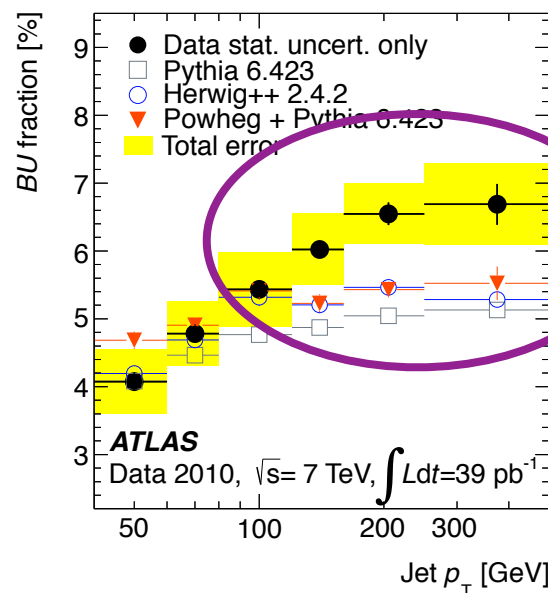
(a)



(b)



(c)



- Interesting excess of (single) b quark jets

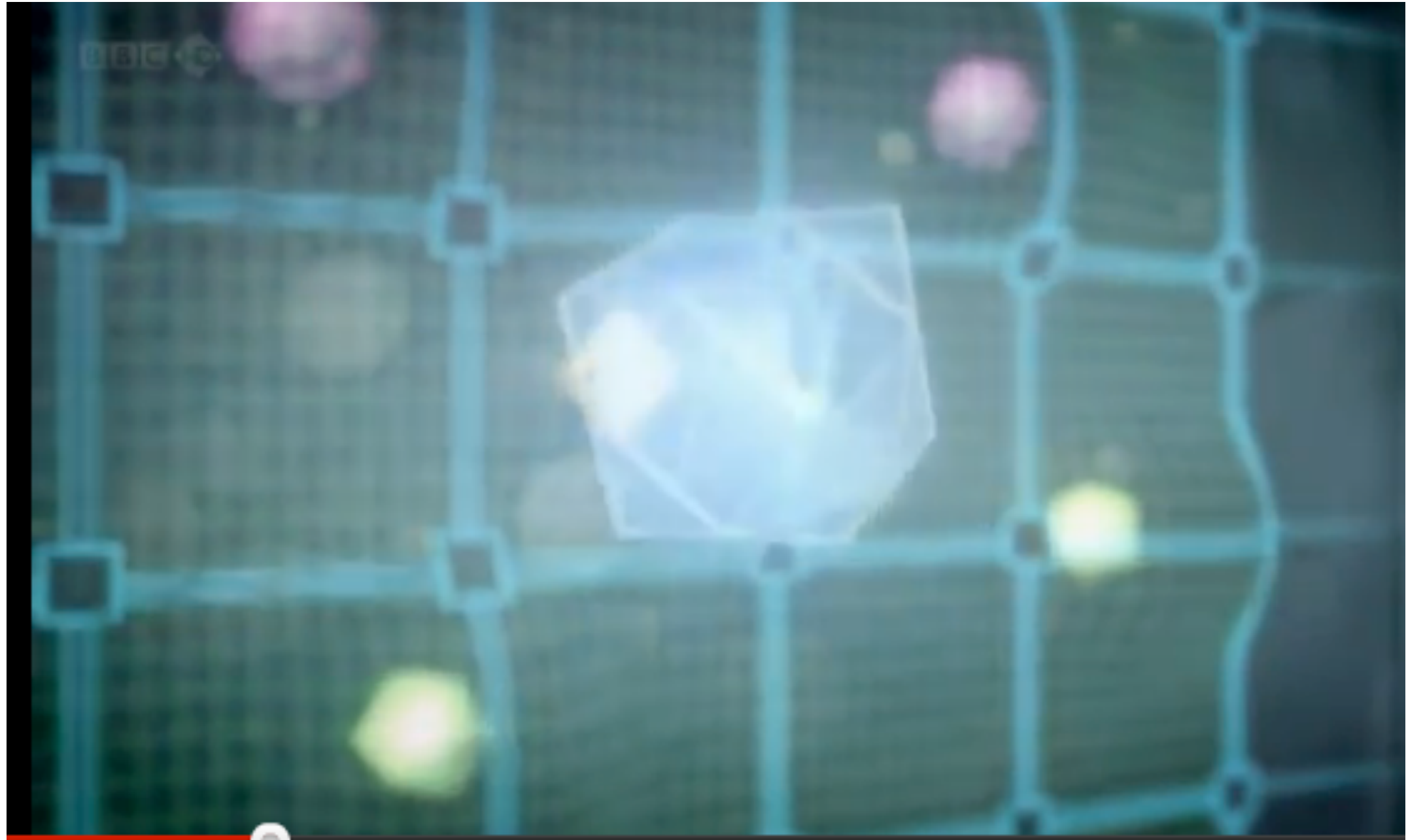
The Higgs Boson

Higgs Boson



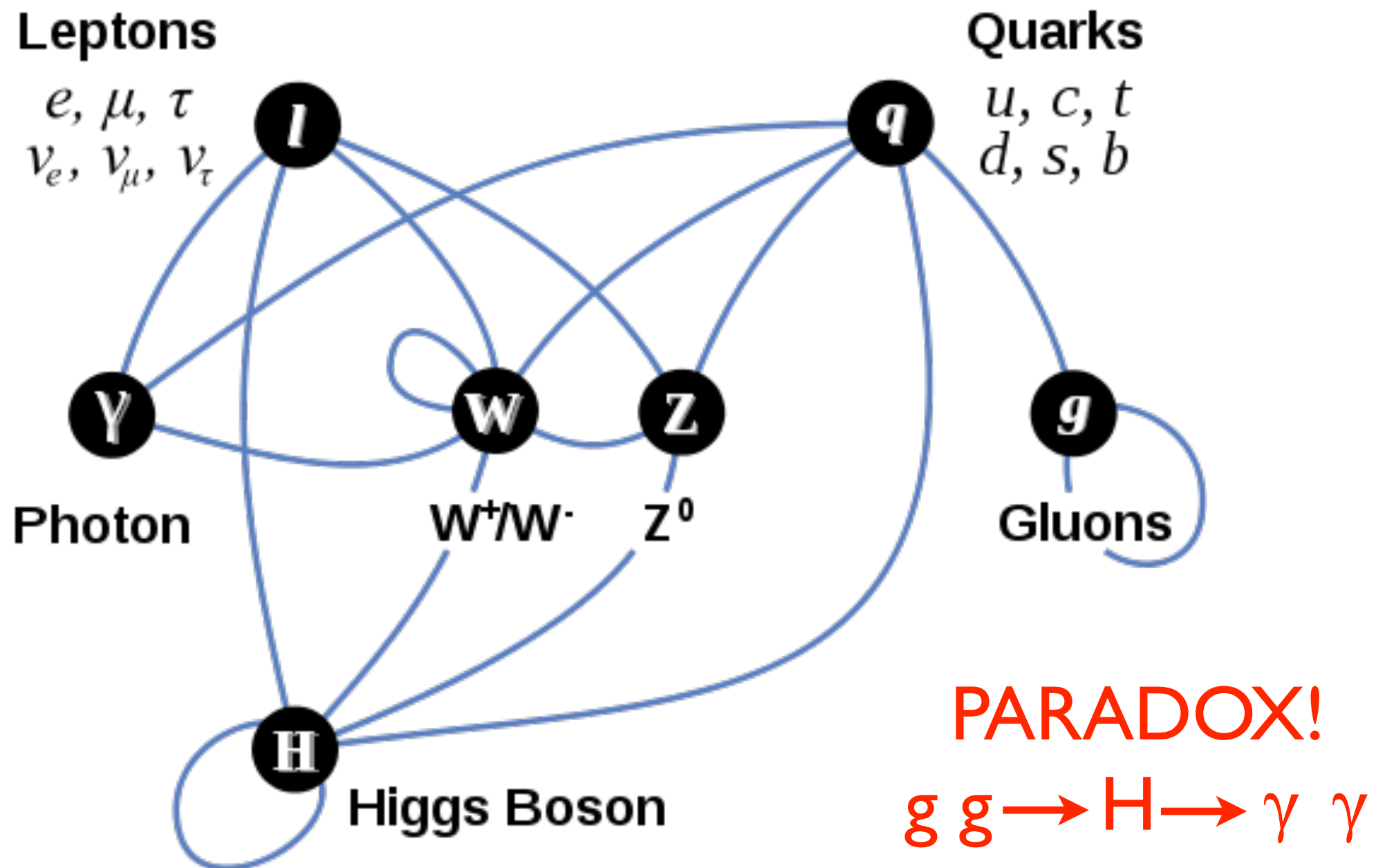
Opening ceremony, Paralympic Games, London, August 2012

Higgs Boson

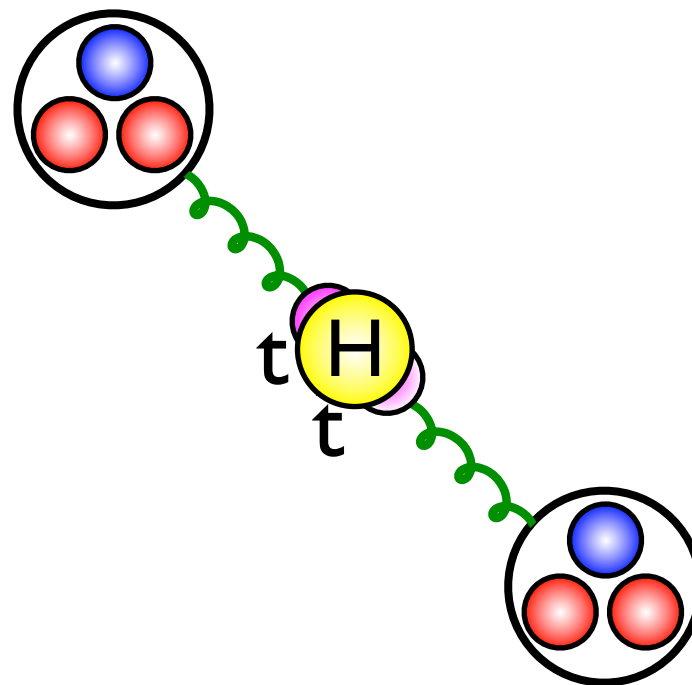


‘The Hunt for the Higgs’, BBC TV, January 2012

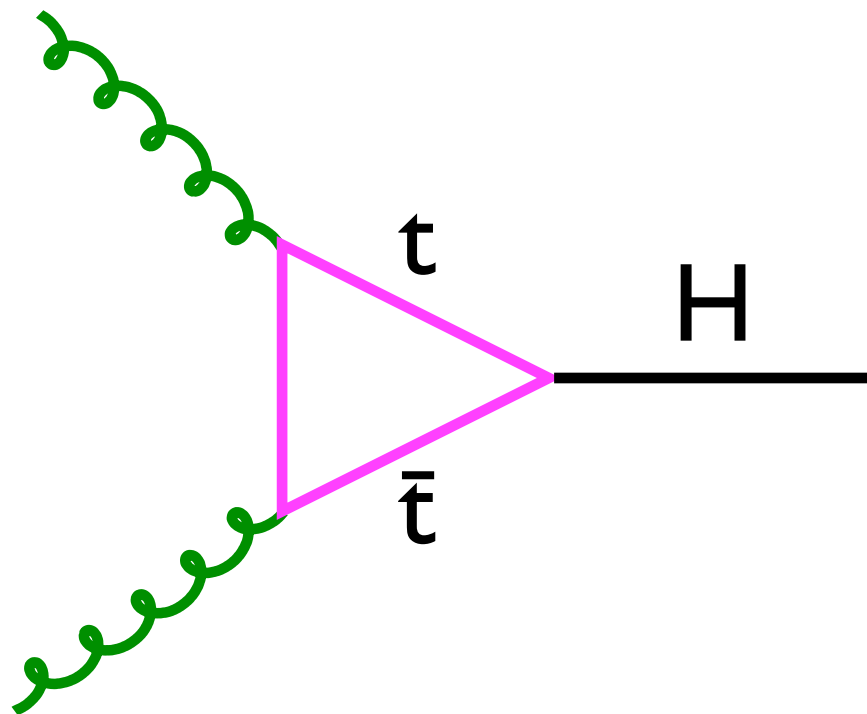
The Standard Model



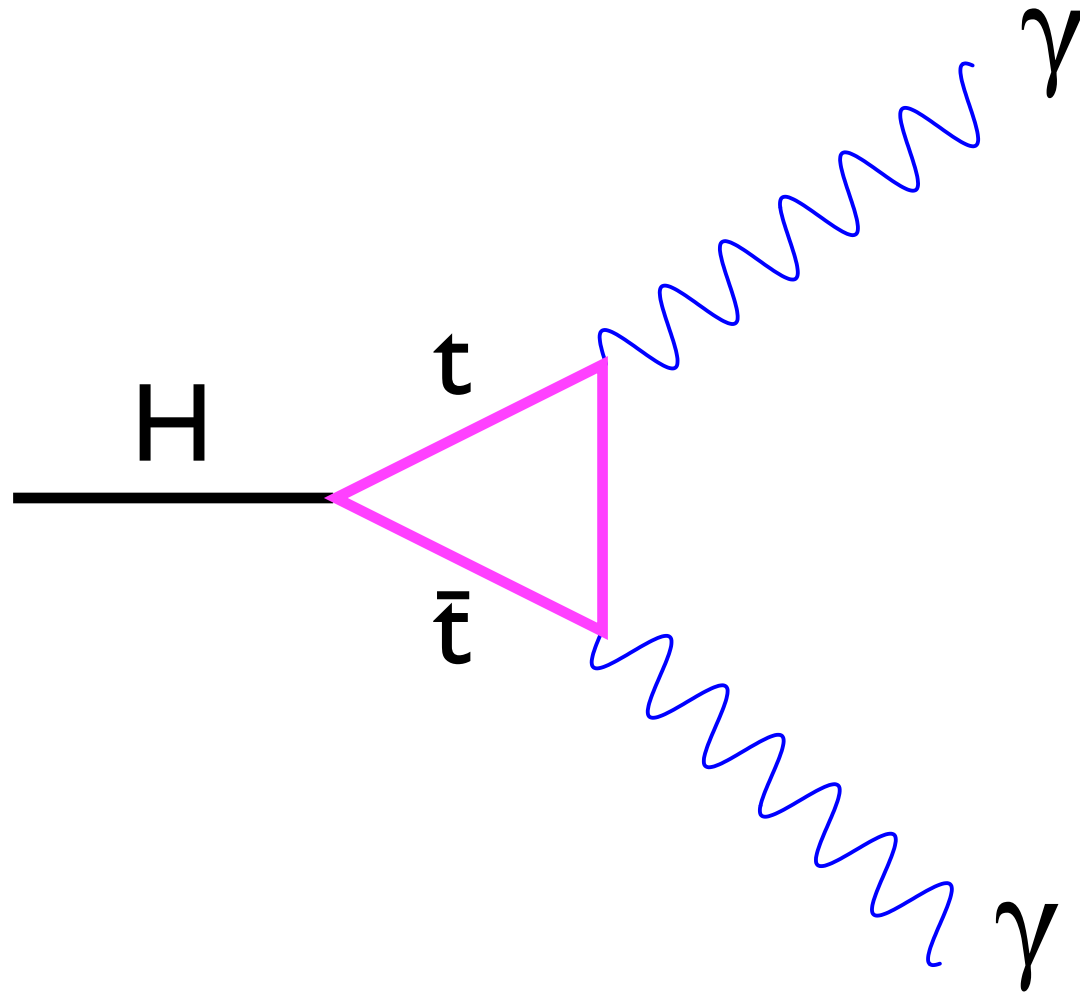
Higgs Production



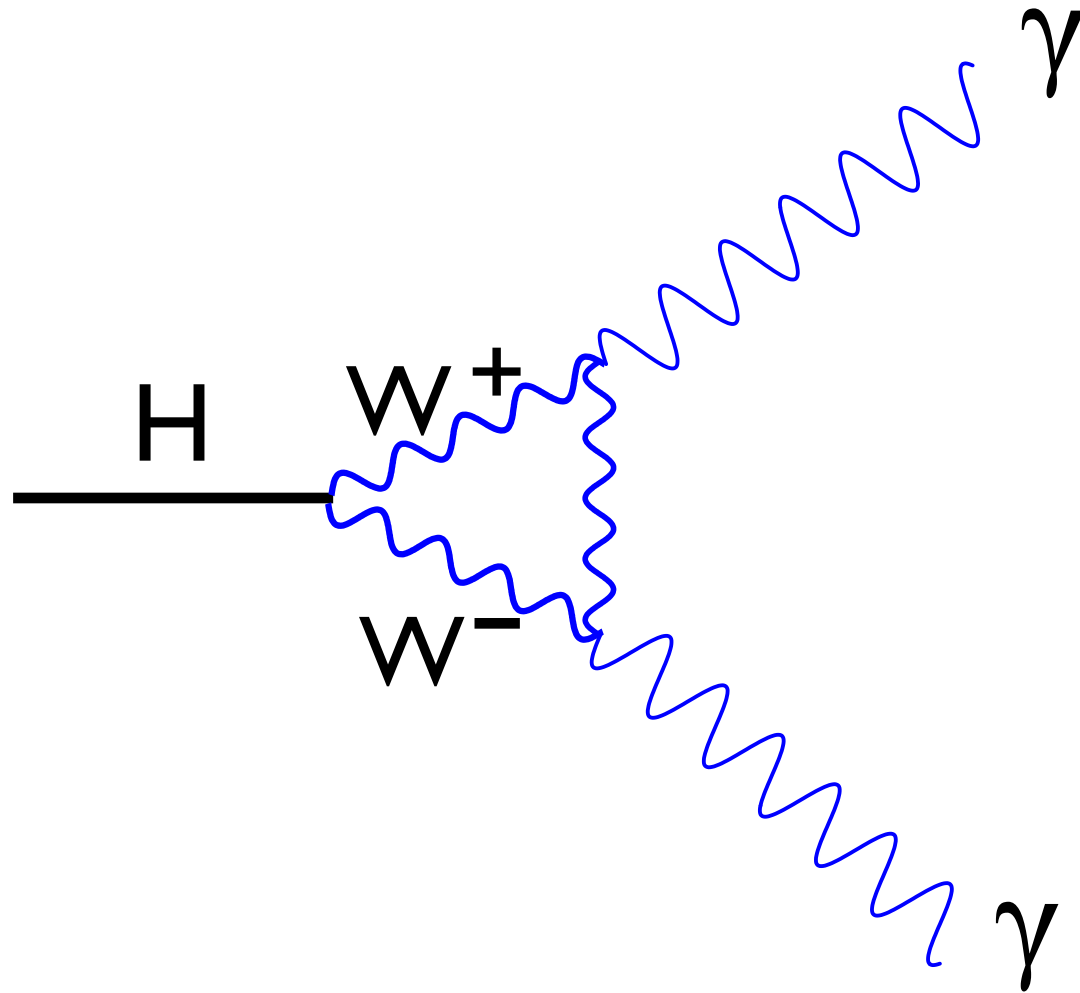
Higgs Production



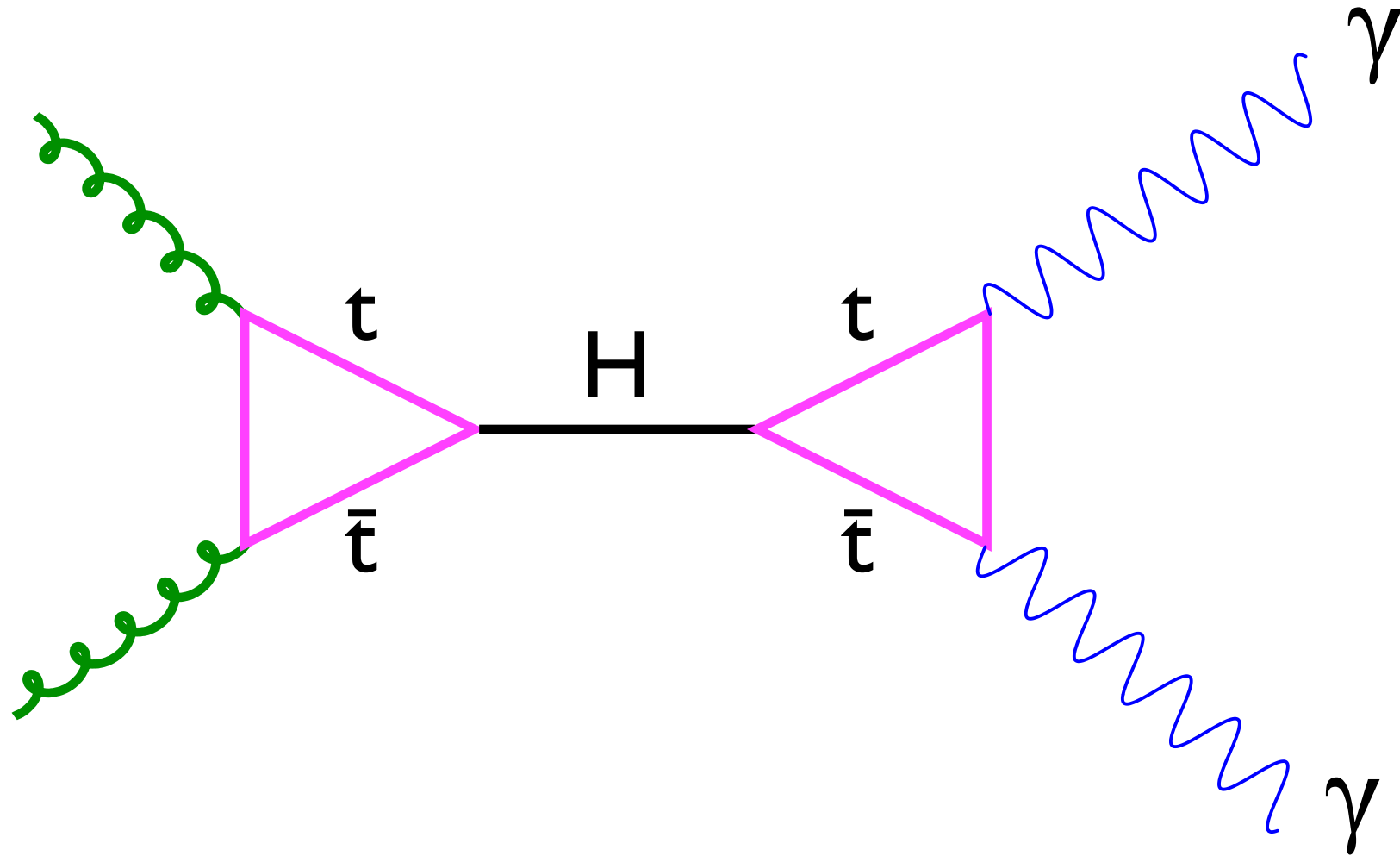
Higgs Decay



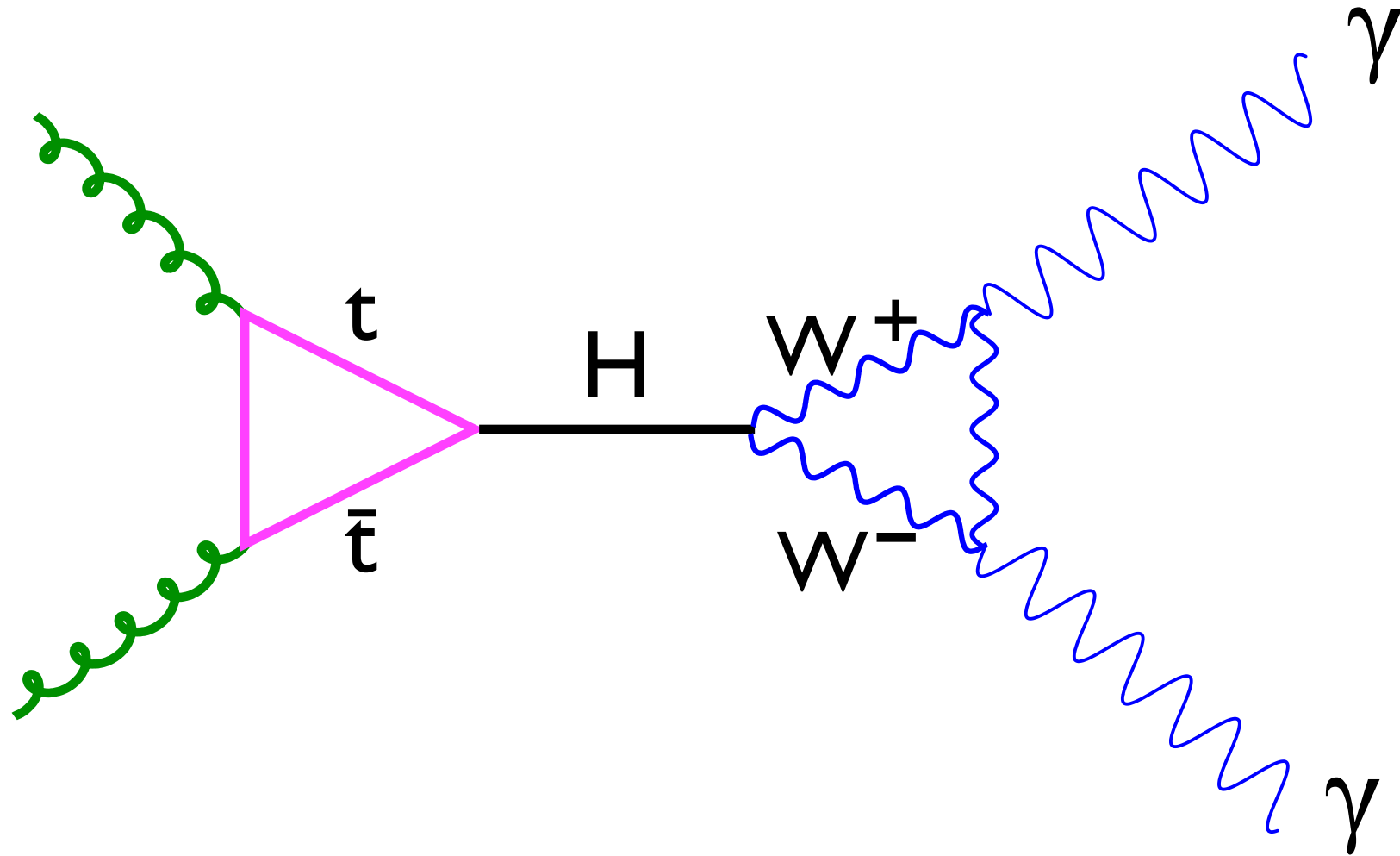
Higgs Decay



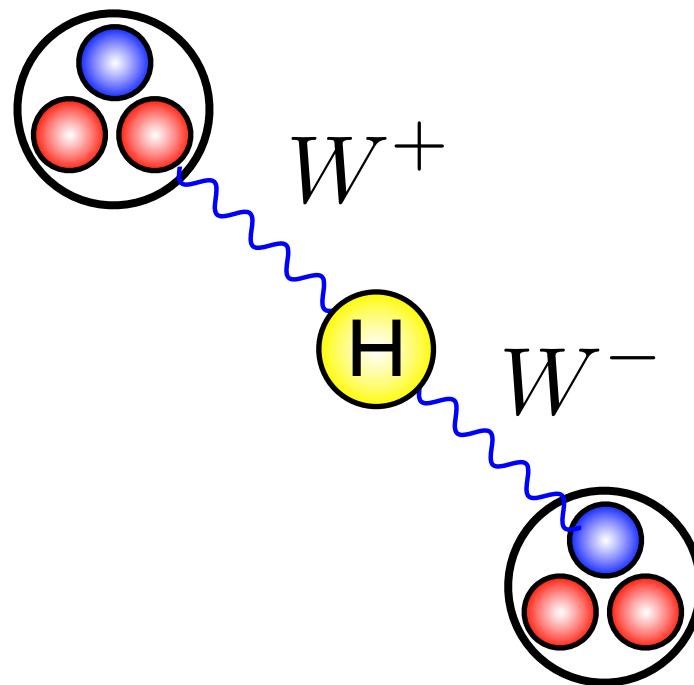
Higgs Production & Decay



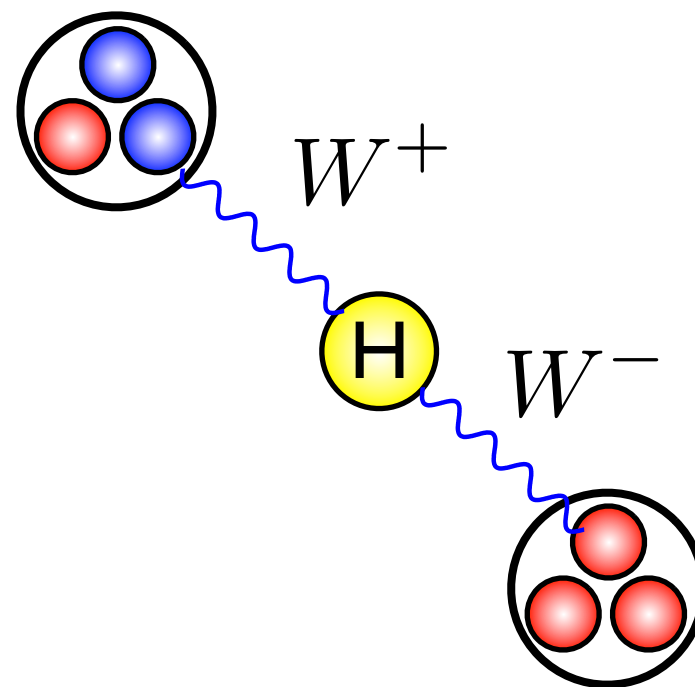
Higgs Production & Decay



Higgs Production by Vector Boson Fusion

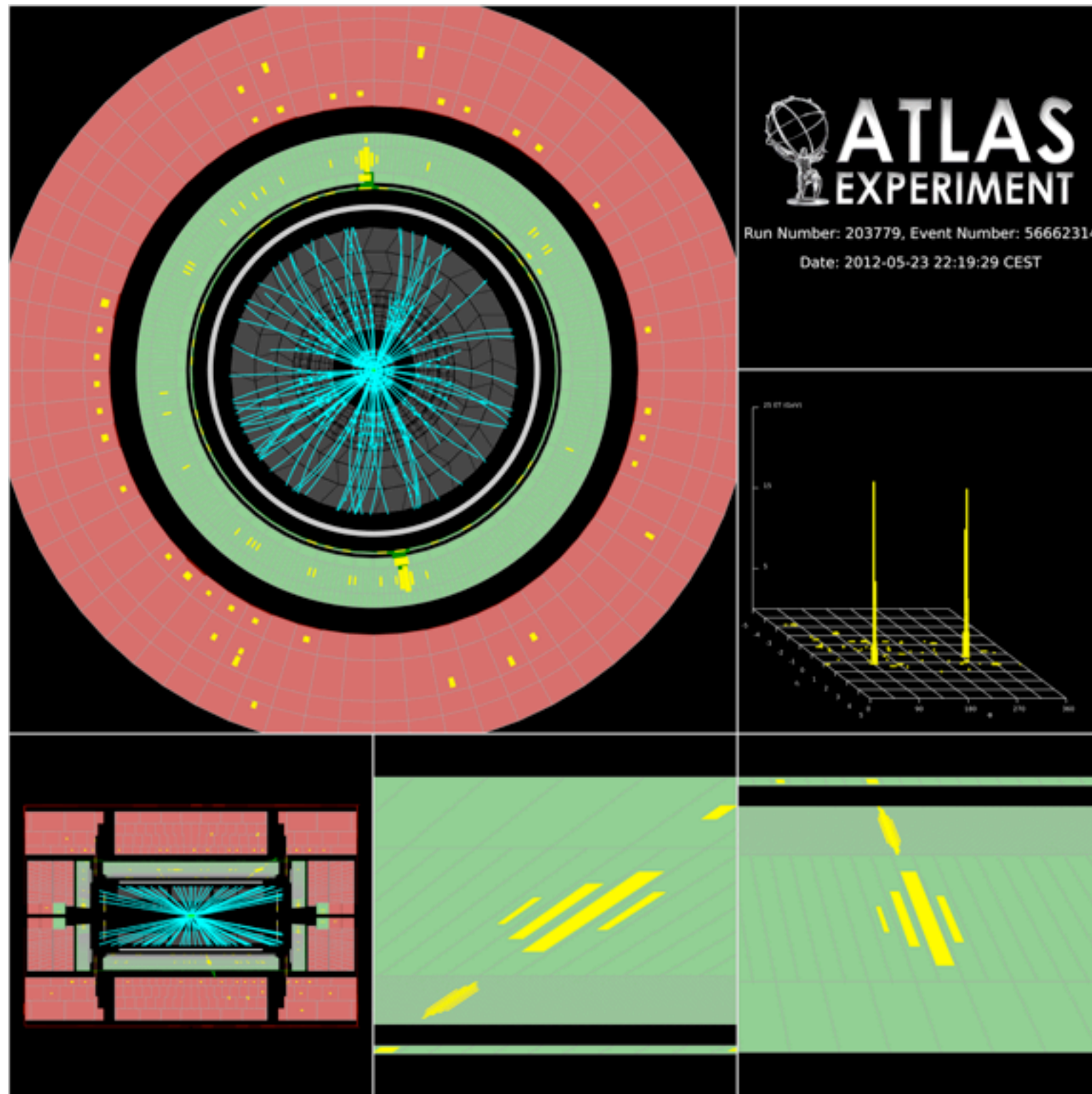


Higgs Production by Vector Boson Fusion



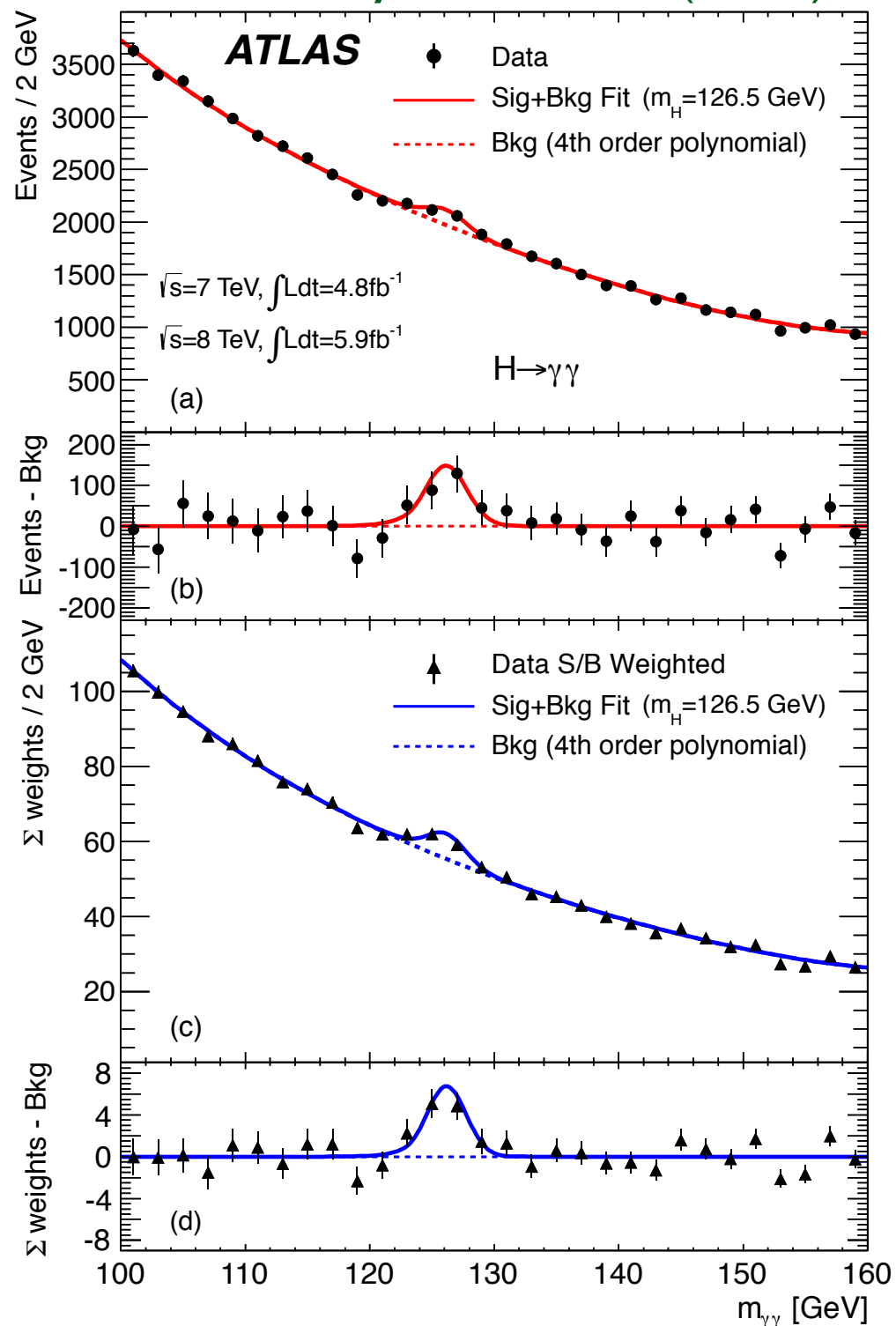
- Forward jets
- Few central jets
- Central jet veto increases S/B

Higgs Production & Decay

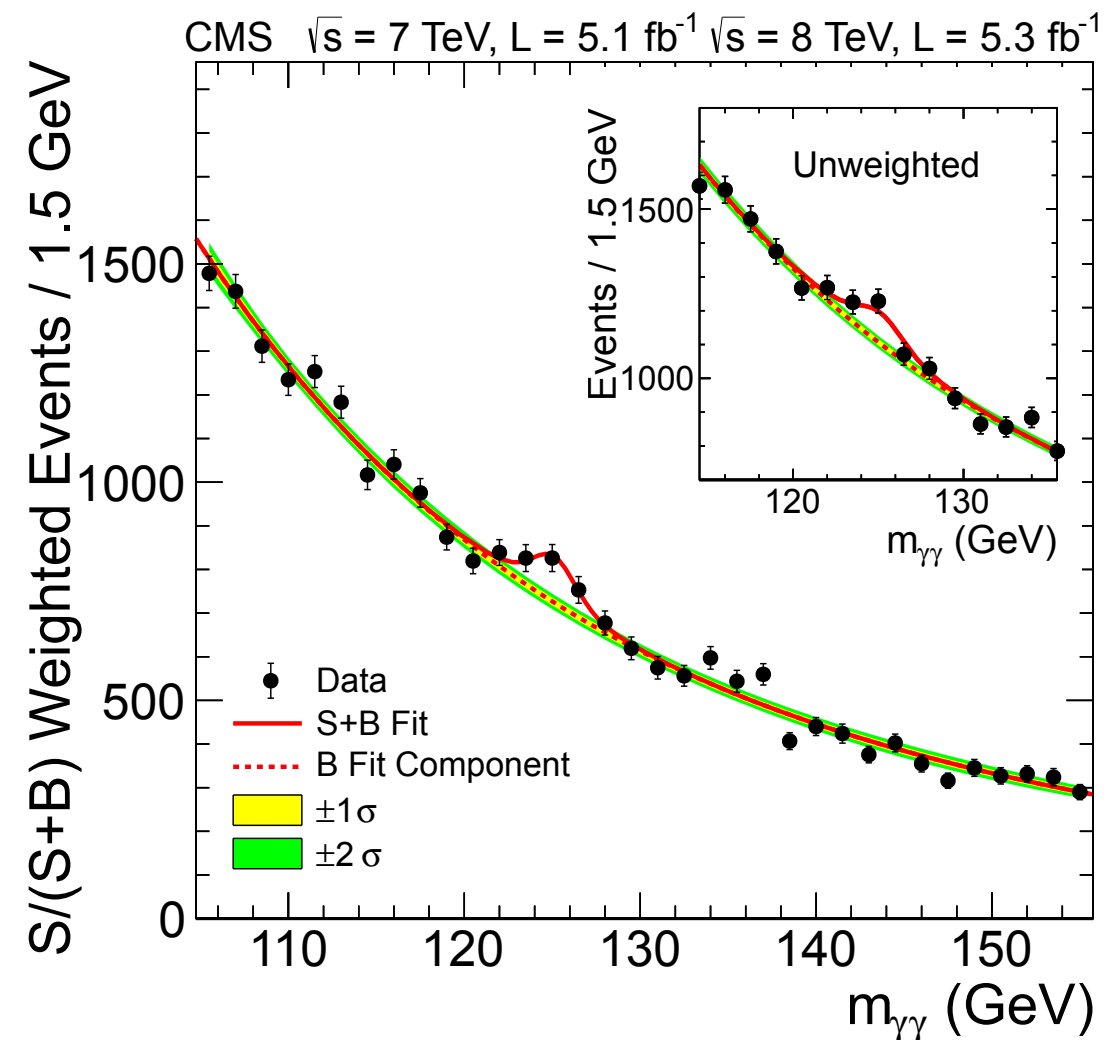


Higgs Production & Decay

ATLAS, Phys.Lett. B716(2012)1



CMS, Phys.Lett. B716(2012)30



ATLAS: $M_x = 126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})$

CMS: $M_x = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})$

HCP Symposium, Nov 2012

Higgs Signal and Background Simulation

Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
W +jets, Z/γ^* +jets	ALPGEN [59]+HERWIG
$t\bar{t}, tW, tb$	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \rightarrow WW$	MC@NLO+HERWIG
$gg \rightarrow WW$	gg2WW [62]+HERWIG
$q\bar{q} \rightarrow ZZ$	POWHEG [63]+PYTHIA
$gg \rightarrow ZZ$	gg2ZZ [64]+HERWIG
WZ	MadGraph+PYTHIA, HERWIG
$W\gamma$ +jets	ALPGEN+HERWIG
$W\gamma^*$ [65]	MadGraph+PYTHIA
$q\bar{q}/gg \rightarrow \gamma\gamma$	SHERPA

ATLAS, Phys.Lett.B716(2012)1

Higgs Production & Decay

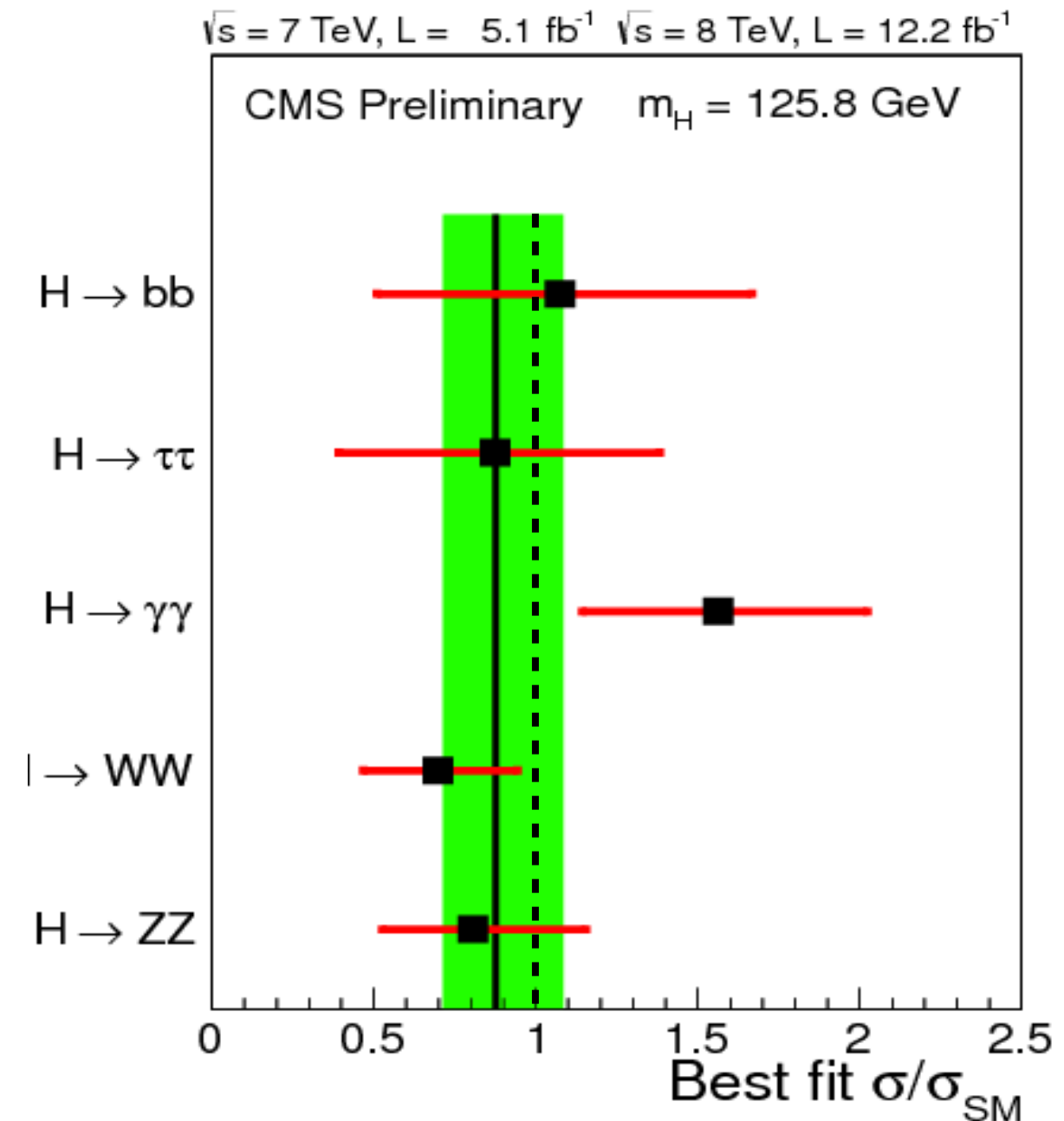
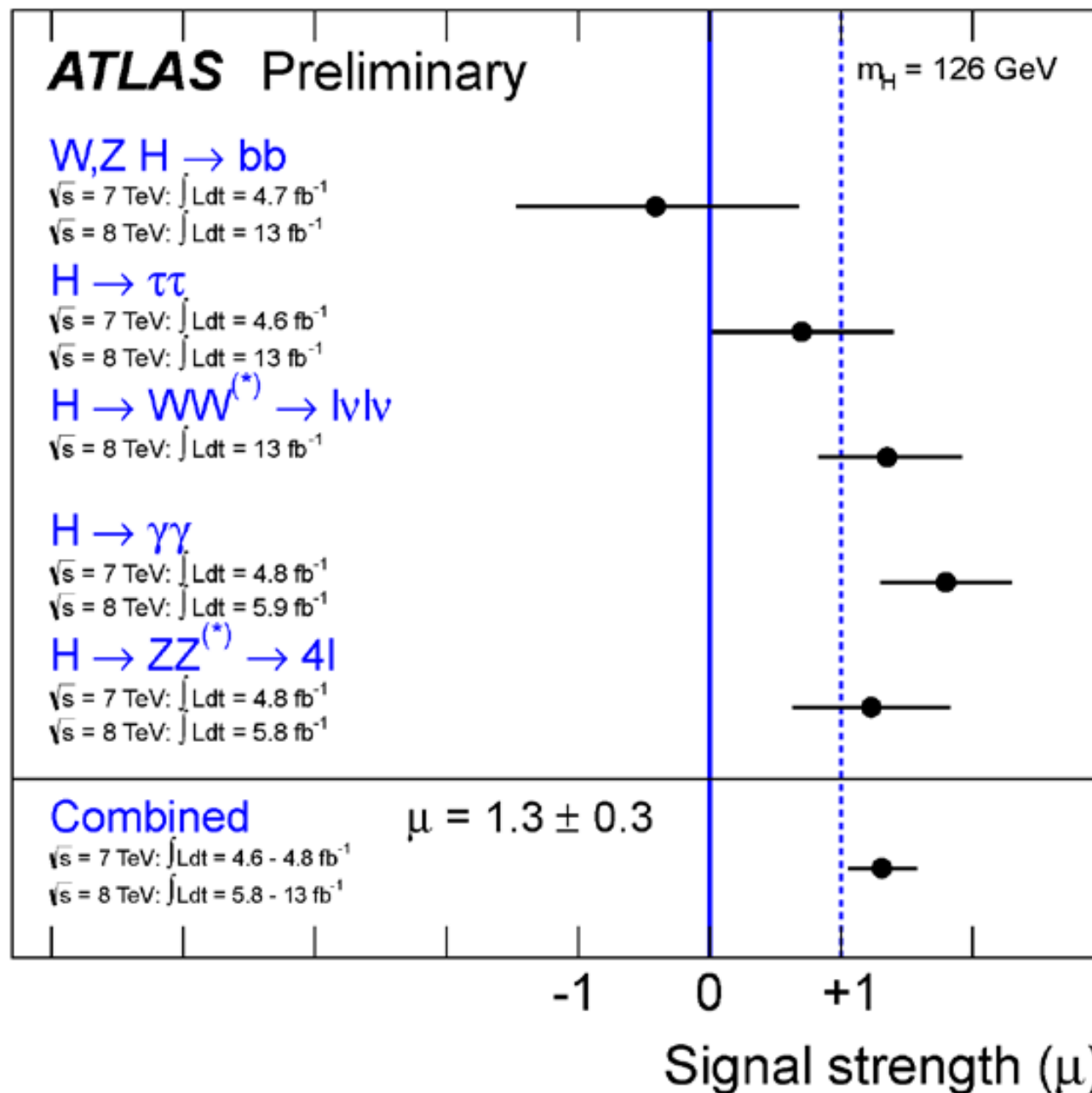
Standard Model predictions for $M_H = 126 \text{ GeV}$:

- $\sigma_{pp \rightarrow H}(7 \text{ TeV}) = 17.5 \text{ pb}$, $\sigma_{pp \rightarrow H}(8 \text{ TeV}) = 22.3 \text{ pb}$
- $\text{Prob}(H \rightarrow \gamma\gamma) = 0.23 \%$
- ➔ $\sigma_{pp \rightarrow H \rightarrow \gamma\gamma}(7 \text{ TeV}) = 39 \text{ fb}$, $\sigma_{pp \rightarrow H \rightarrow \gamma\gamma}(8 \text{ TeV}) = 50 \text{ fb}$
- ➔ 80+110 events after selection cuts and detector efficiencies

Both ATLAS and CMS saw some excess

Ratios to Standard Model

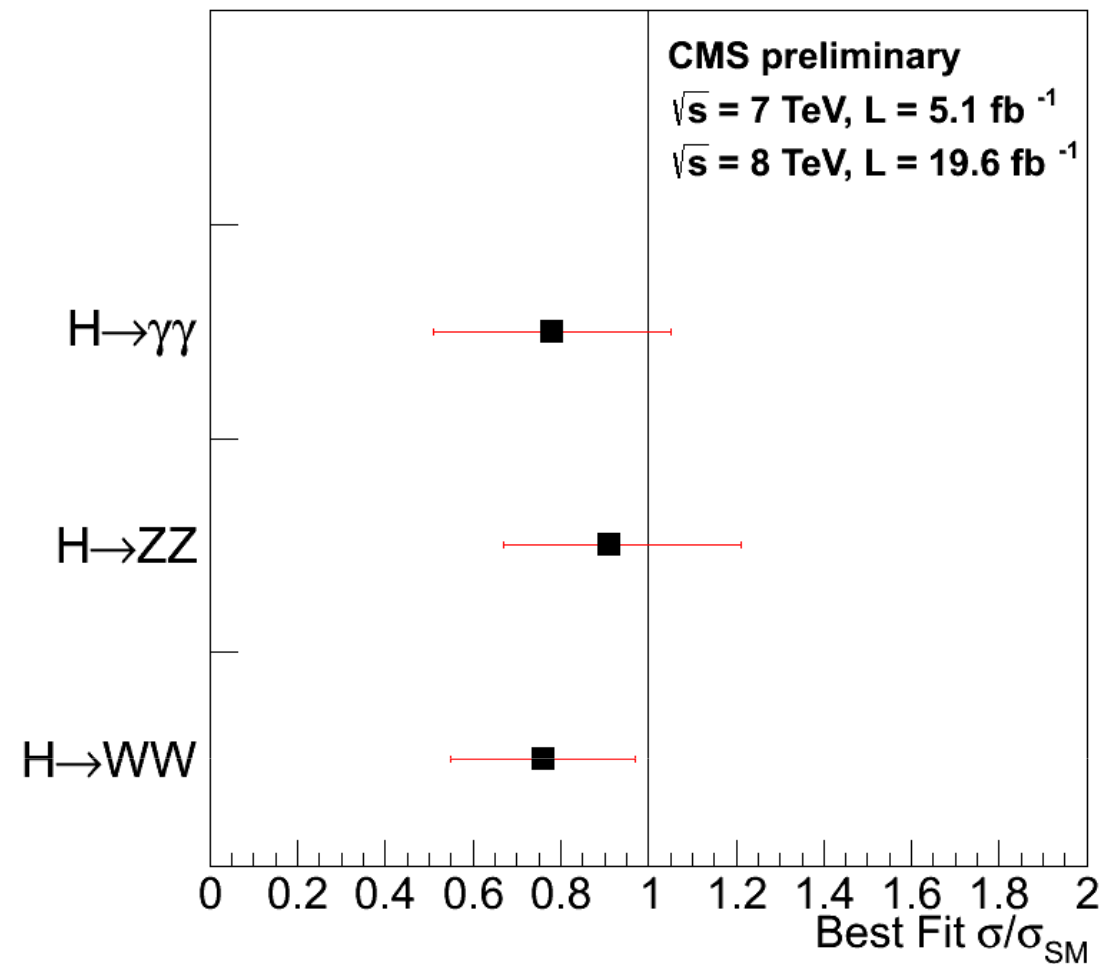
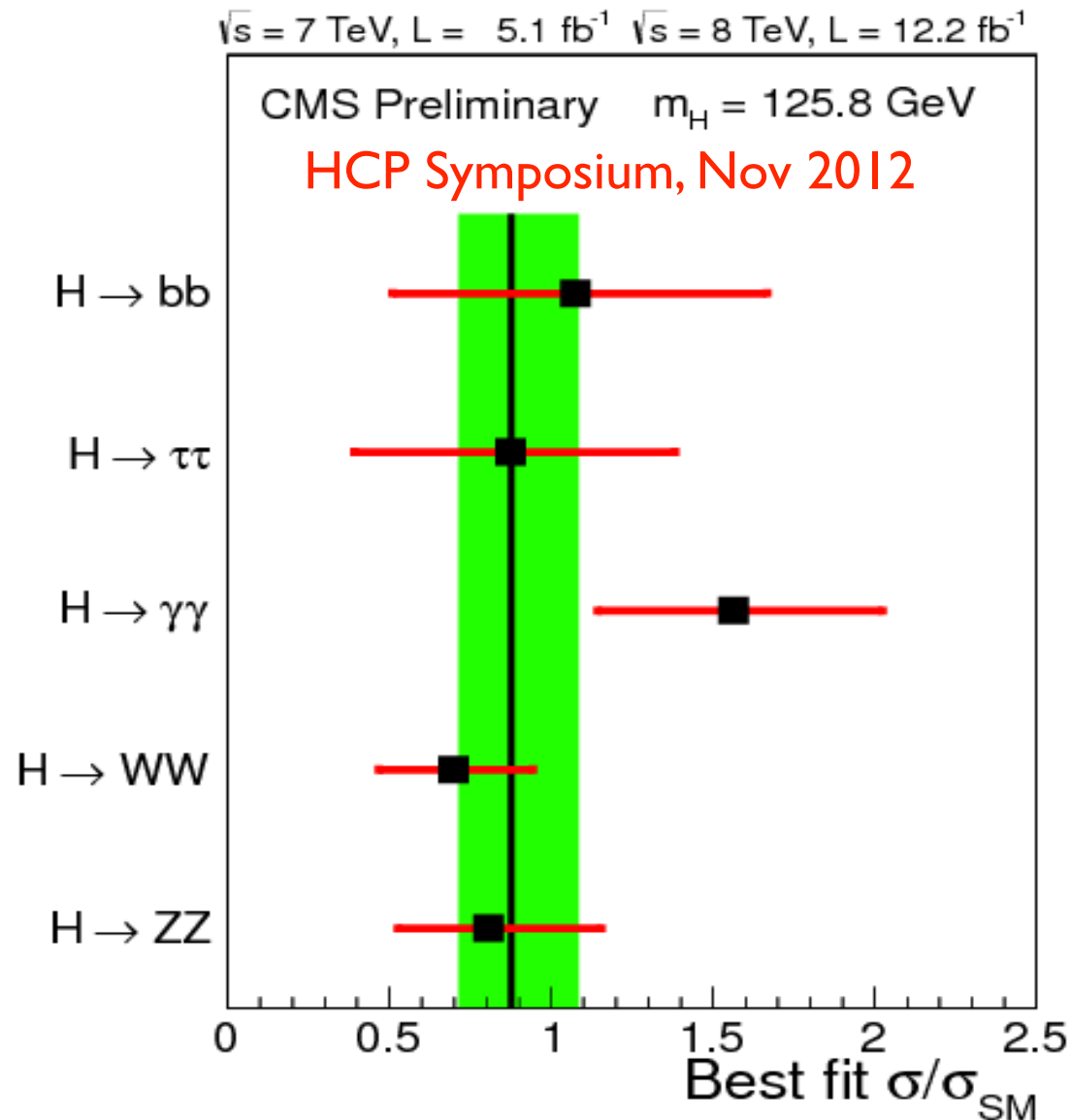
HCP Symposium, Nov 2012



- No sign (yet) of **significant** deviations from Standard Model

CMS Higgs Update

C. Ochoa, Moriond, March 2013



● $\gamma\gamma$ excess went away!

$$m_H = 125.8 \pm 0.5 \text{ (stat.)} \pm 0.2 \text{ (syst.)} \quad H \rightarrow ZZ \rightarrow 4l$$

$$m_H = 125.4 \pm 0.5 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \quad H \rightarrow \gamma\gamma$$

$$m_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$$

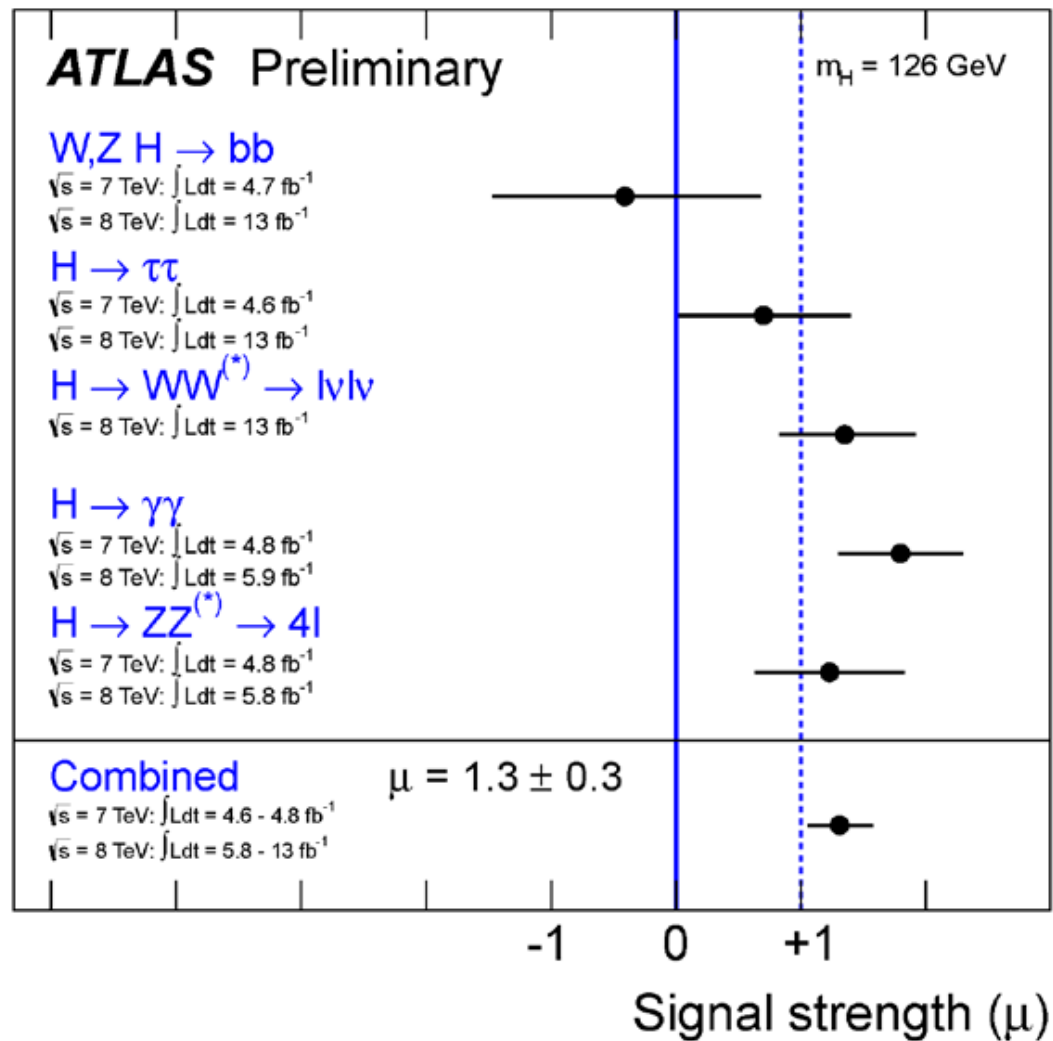
Significance of observation:

- $H \rightarrow ZZ \rightarrow 4l$: 6.7 σ (7.2 exp.)
- $H \rightarrow WW$: 4.1 σ (5.1 exp.)
- $H \rightarrow \gamma\gamma$: 3.2 σ (4.2 exp.)

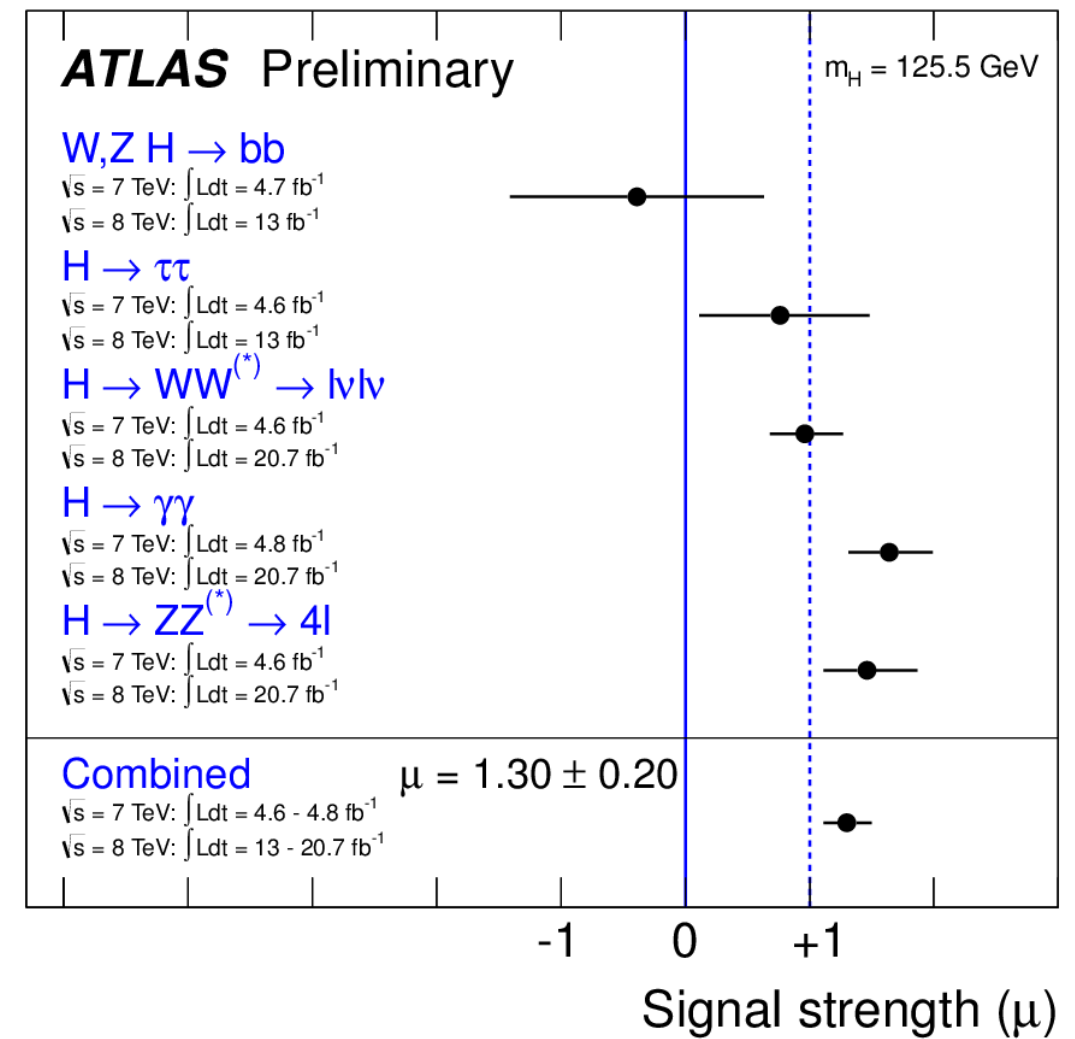
$$\sigma/\sigma_{SM} = .88 \pm 0.21$$

ATLAS Higgs Update

HCP Symposium, Nov 2012



T. Adye, Moriond, March 2013



$$m_H = 125.5 \pm 0.2 \text{ (stat)} \pm_{-0.6}^{+0.5} \text{ (sys)} \text{ GeV}$$

To Be Confirmed

- Spin and parity 0^+ : correlations in VV^* decays
- Production mechanisms: gg, VBF, WH, ZH, ttH
- Self-coupling (HH production): **difficult at LHC**
- Total width 4.2 MeV: **impossible?**
- Decay fractions:

$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

Achievable Precision?

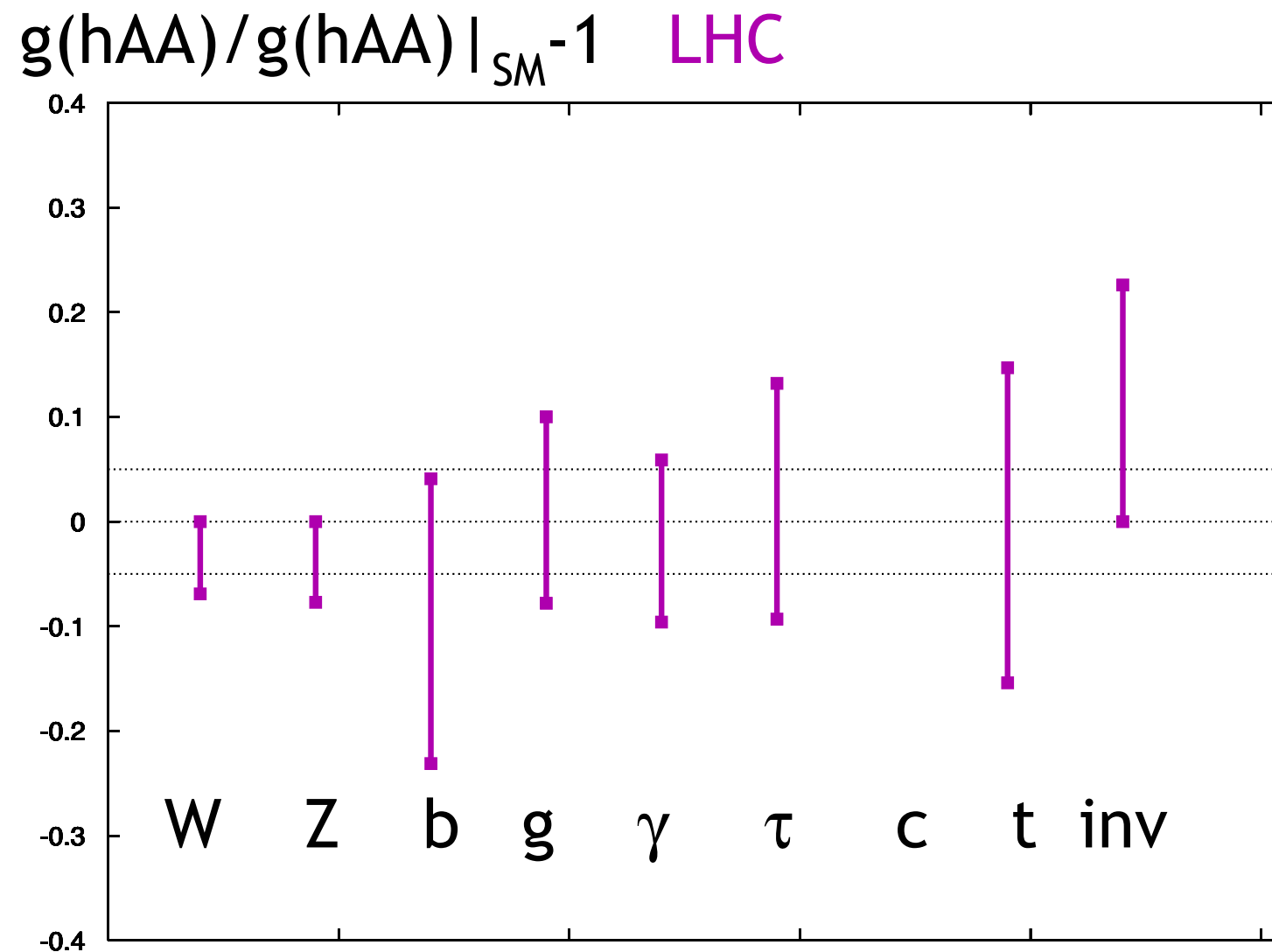


Figure 1: Capabilities of LHC for model-independent measurements of Higgs boson couplings. The plot shows 1σ confidence intervals for LHC at 14 TeV with 300 fb^{-1} . No error is estimated for $g(hcc)$. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

M Peskin, arXiv:1207.2516

Achievable Precision?

$g(hAA)/g(hAA)|_{SM}^{-1}$ LHC / ILC1 / ILC / ILCTeV

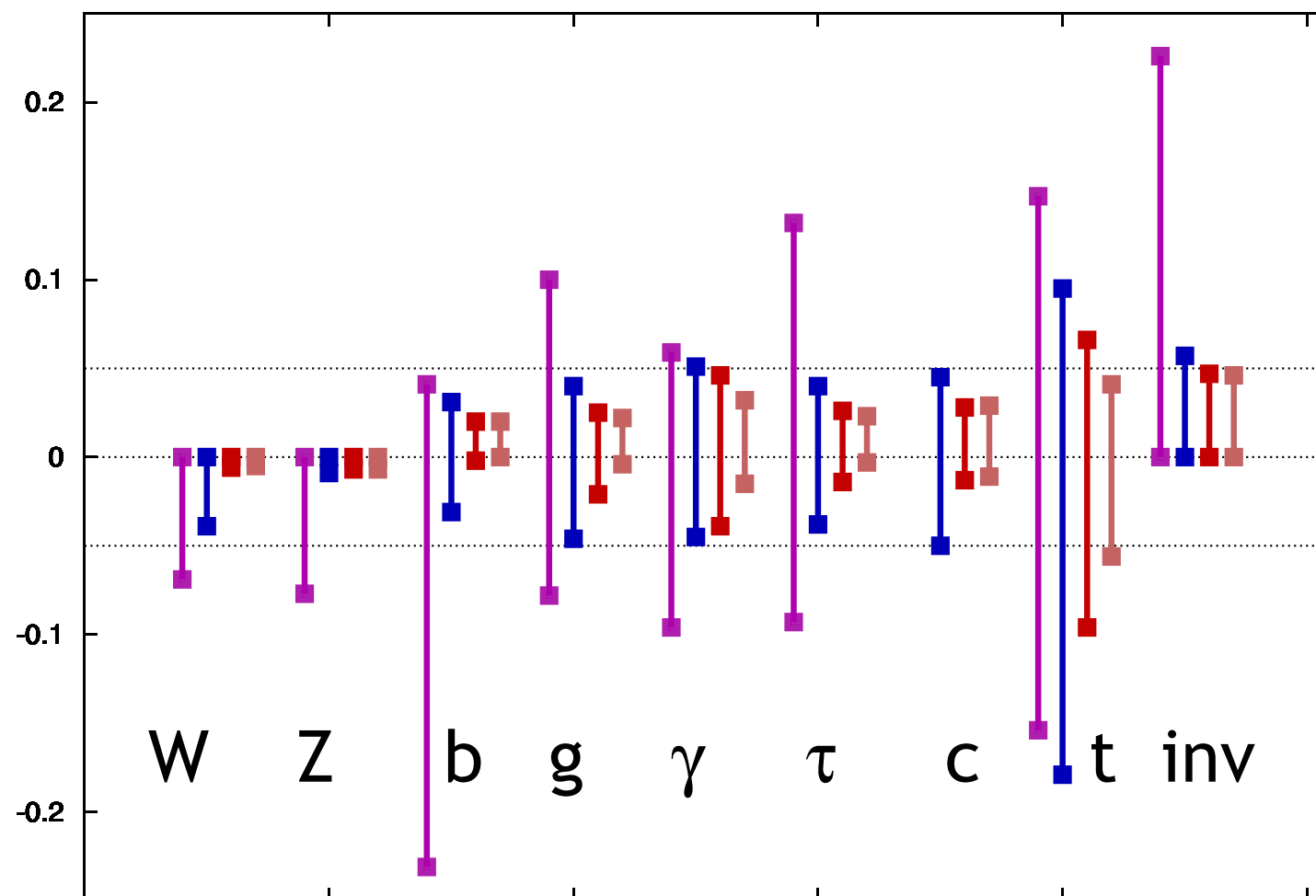


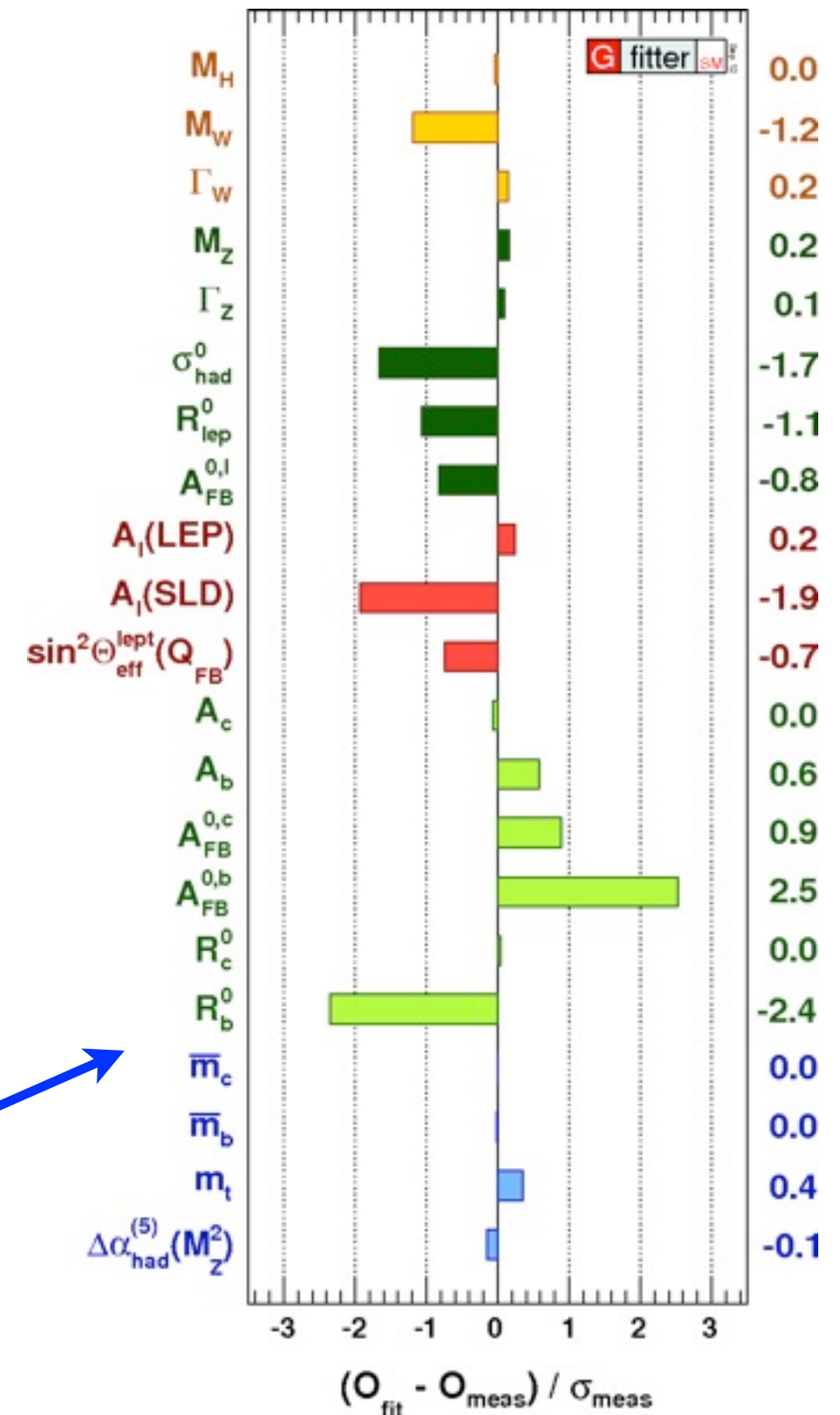
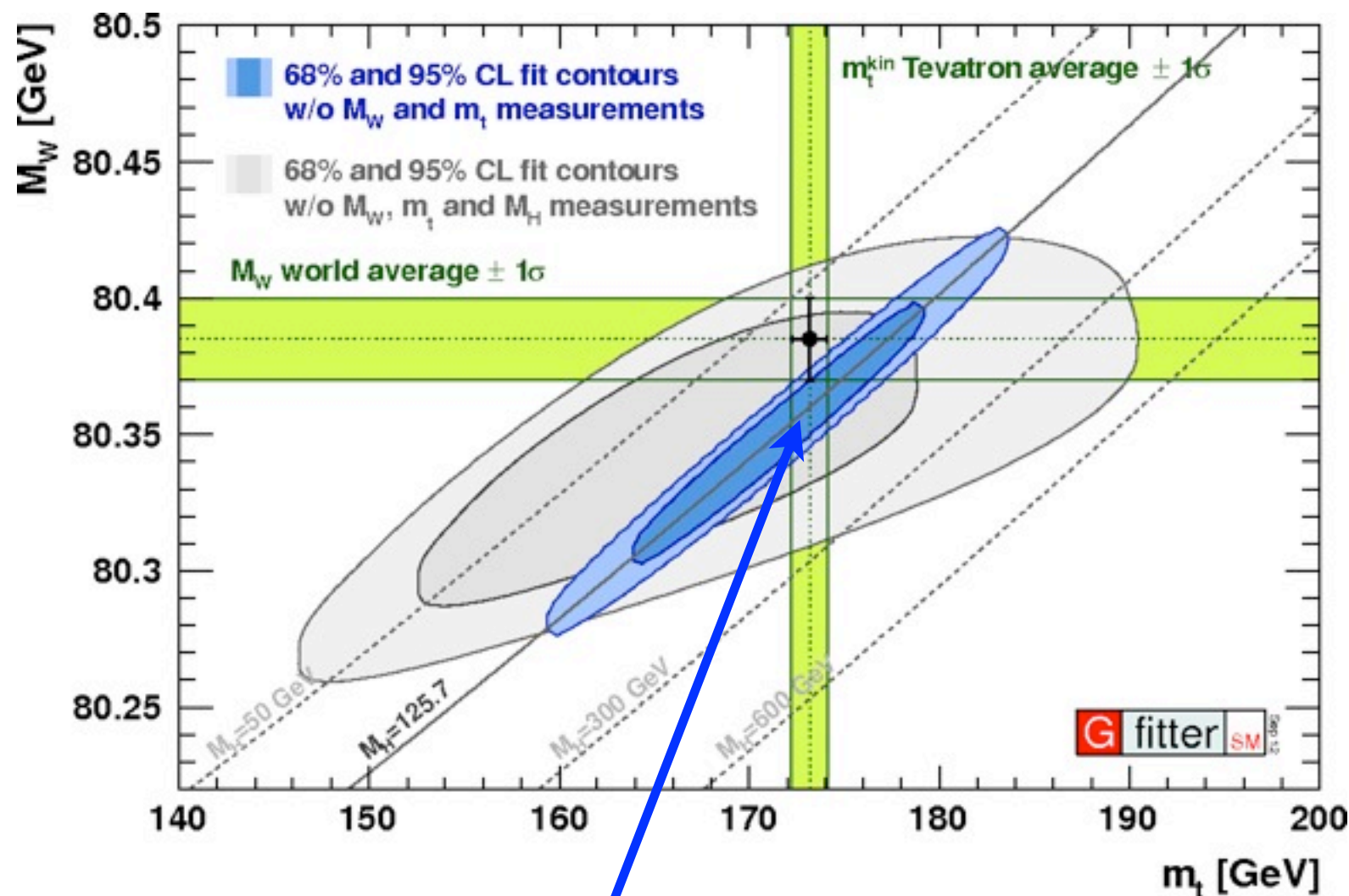
Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1σ confidence intervals for LHC at 14 TeV with 300 fb^{-1} , for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

M Peskin, arXiv:1207.2516

Status of the Standard Model

- It is a respectable (**renormalizable**) quantum field theory
- All predicted relationships between measurable quantities are calculable (in principle)
- Calculations need a short-distance (high-energy) cutoff, but are not sensitive to its scale or nature, as long as it respects SM symmetries
- So a finite high-energy theory (**ultraviolet completion**) is implicitly assumed
- So far, predicted relationships are in satisfactory agreement with experiment (I believe)

Consistency of SM

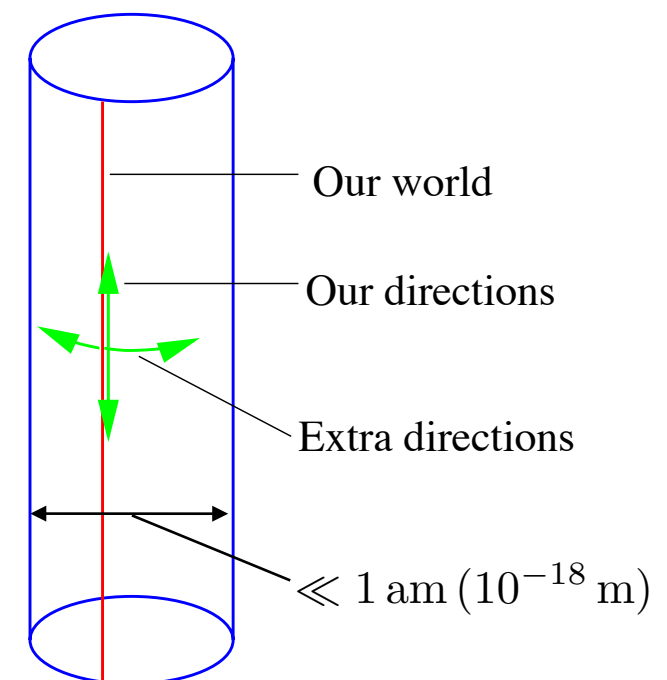
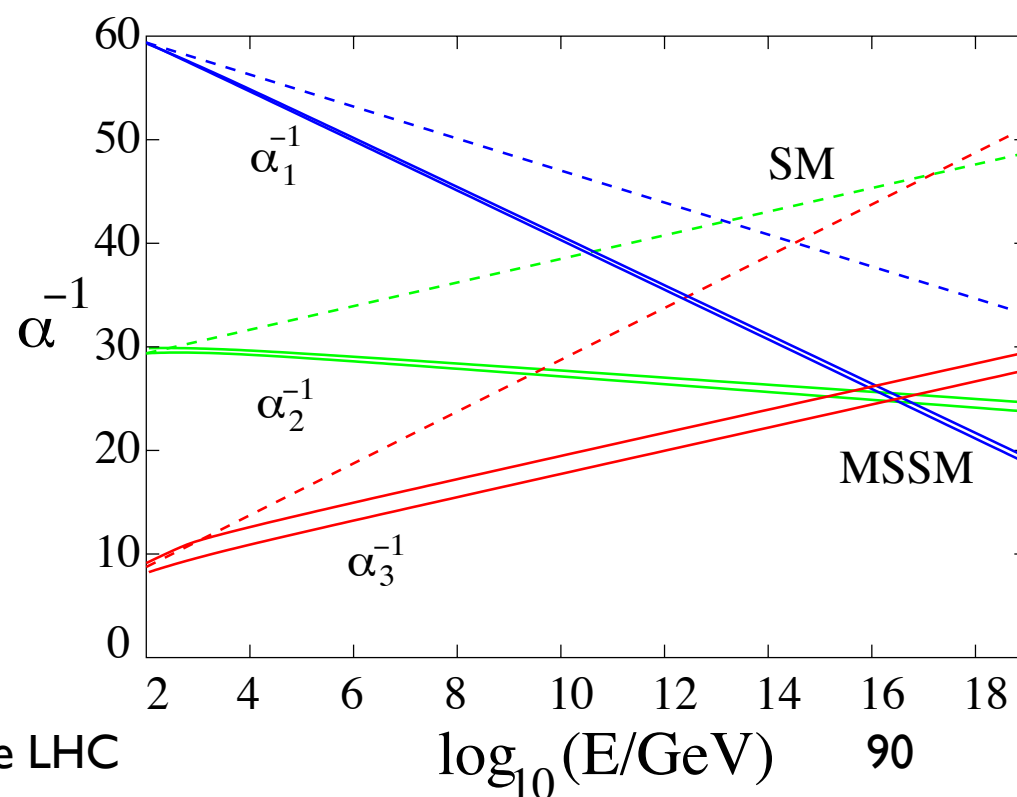


- M_W, m_t predicted from M_H
- Pulls on observables

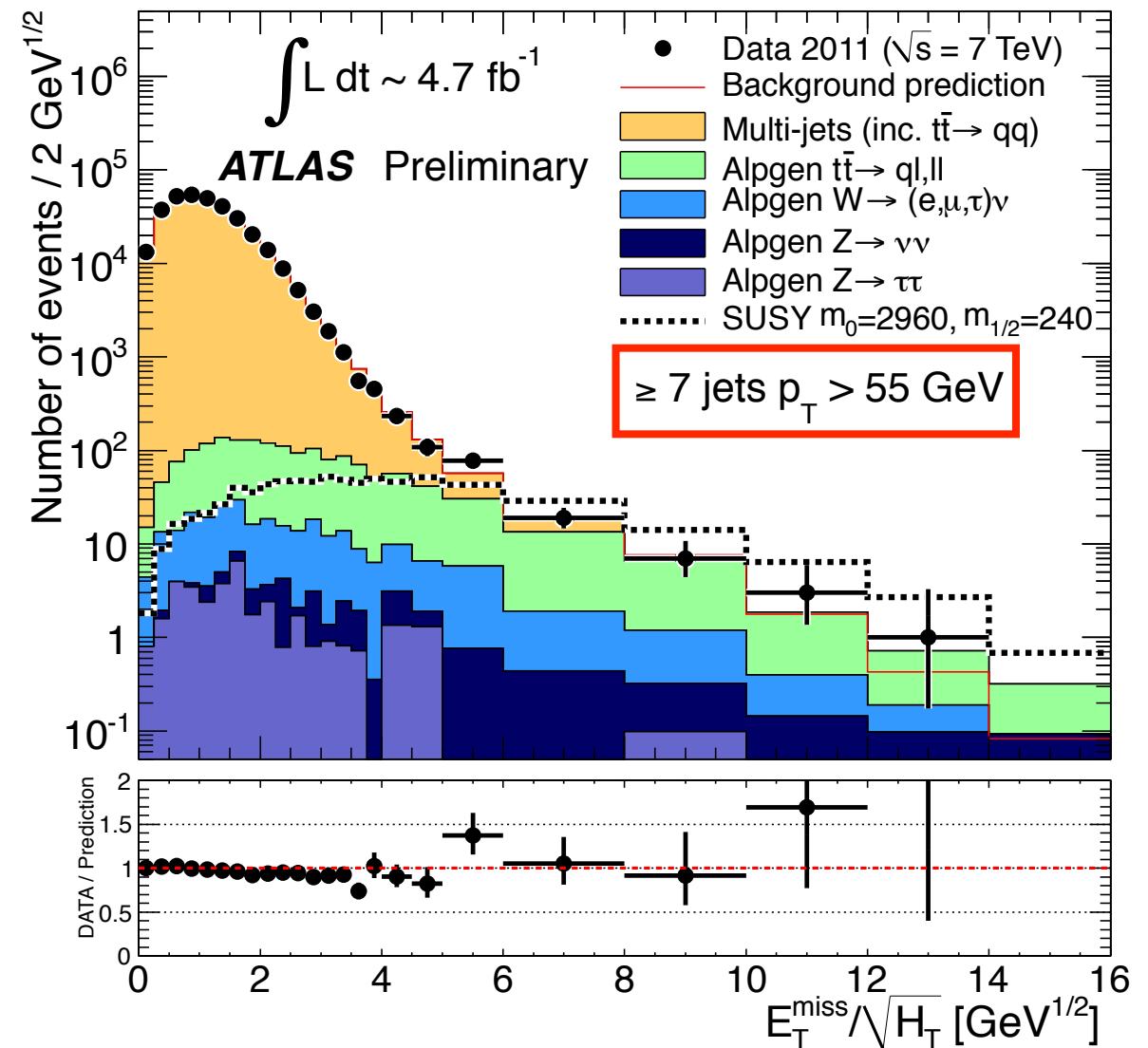
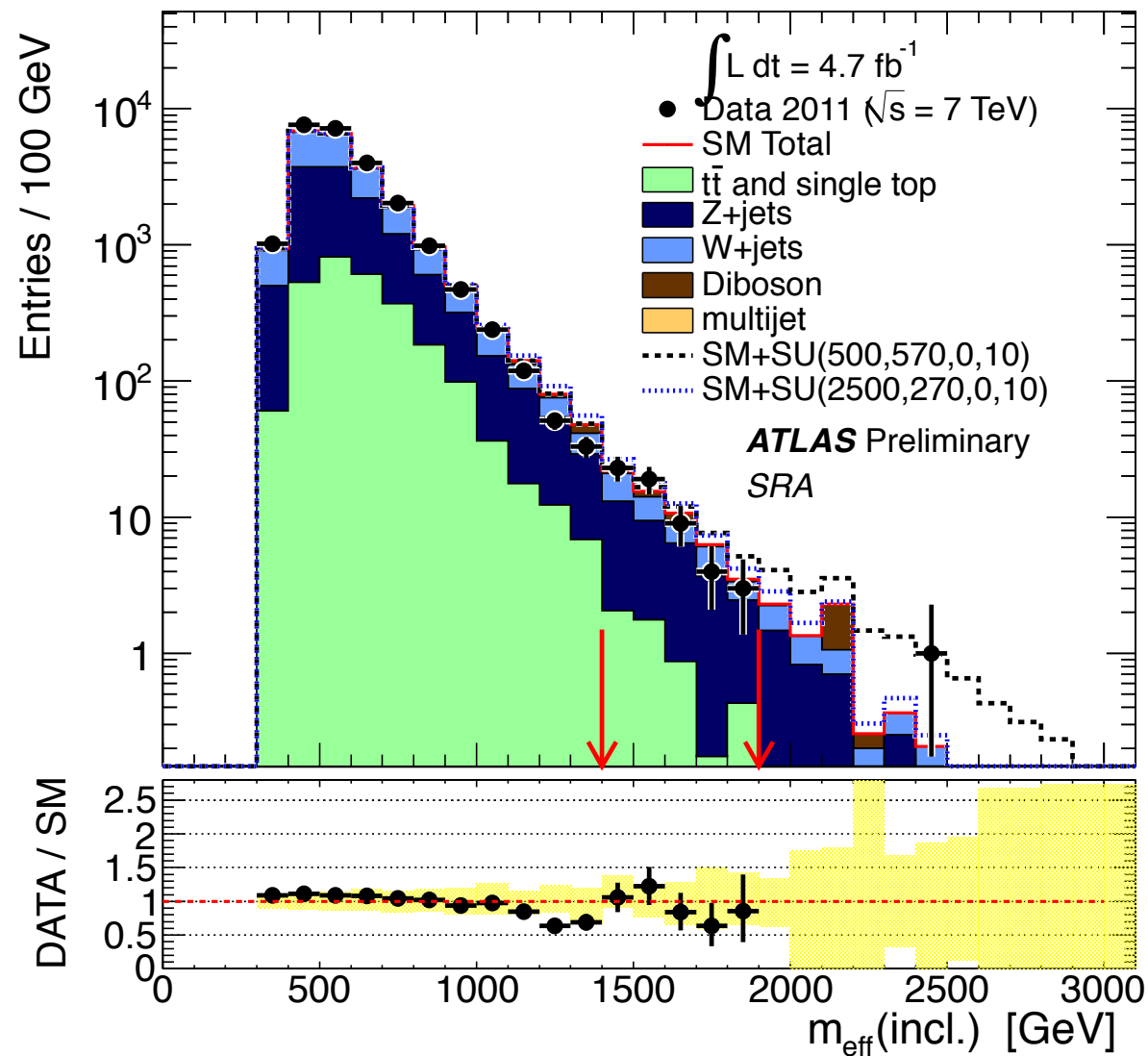
Beyond the Standard Model?

Why BSM?

- The Standard Model is incomplete
 - ✧ No Dark Matter or Dark Energy (95% of Universe)
 - ✧ No neutrino masses
 - ✧ Not enough matter-antimatter asymmetry
 - ✧ No unification of fundamental forces
- New phenomena at TeV scale could solve these
 - ✧ Leading ideas: Supersymmetry and Extra Dimensions

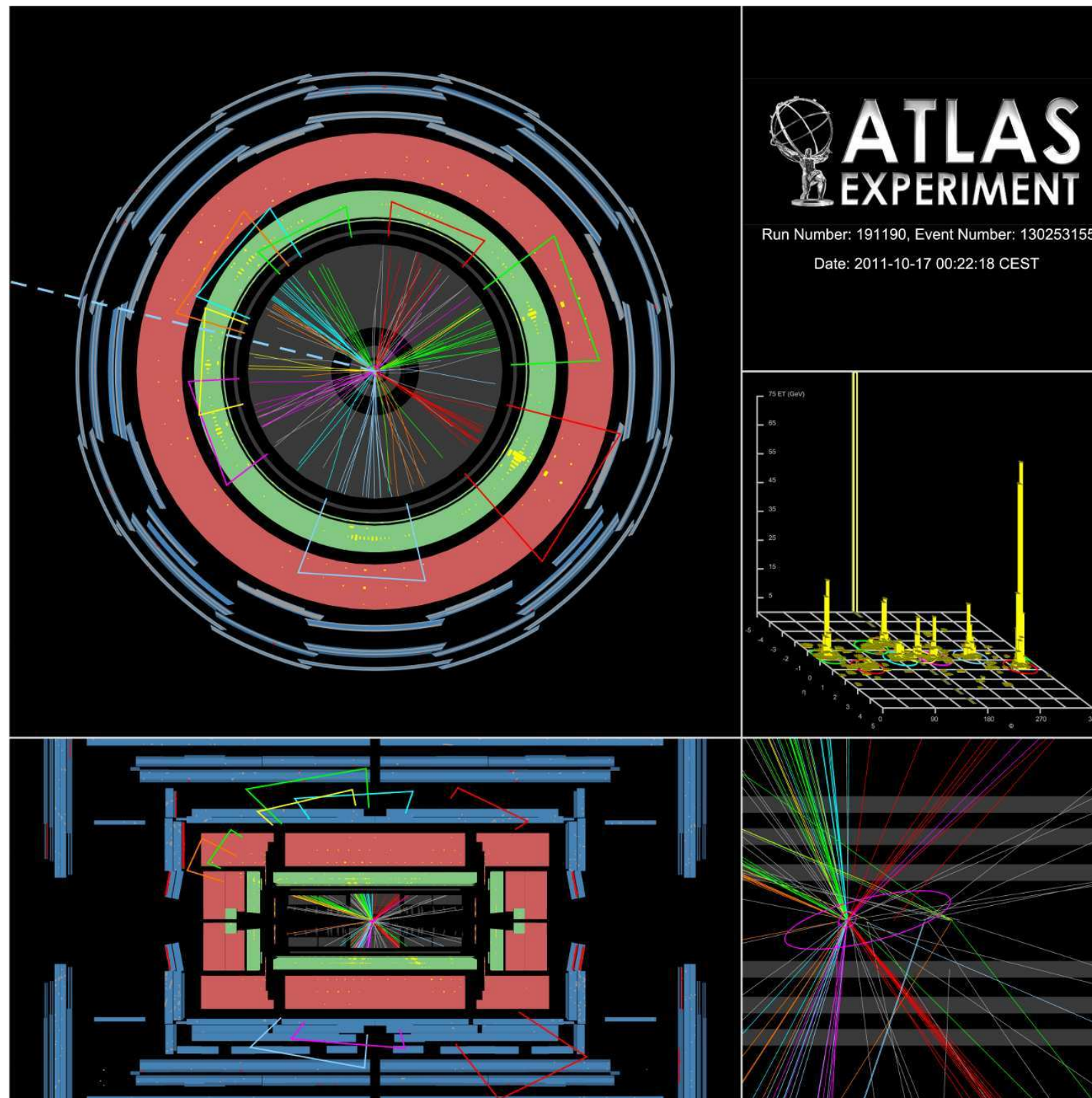


Searching for new signals



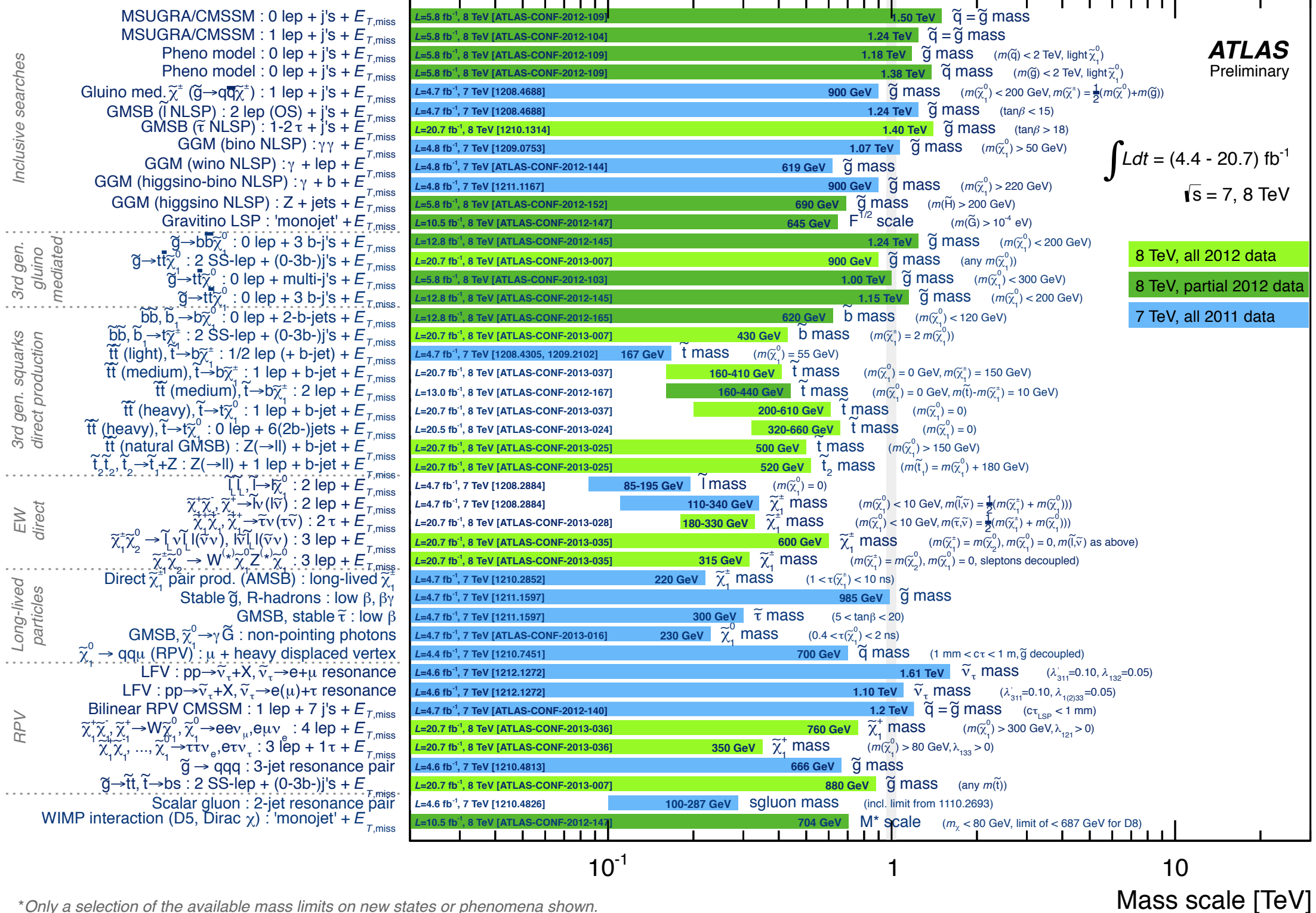
- “SUSY” = Constrained Minimal Supersymmetric Standard Model
- Huge parameter space still to explore

A 7-Jet Event



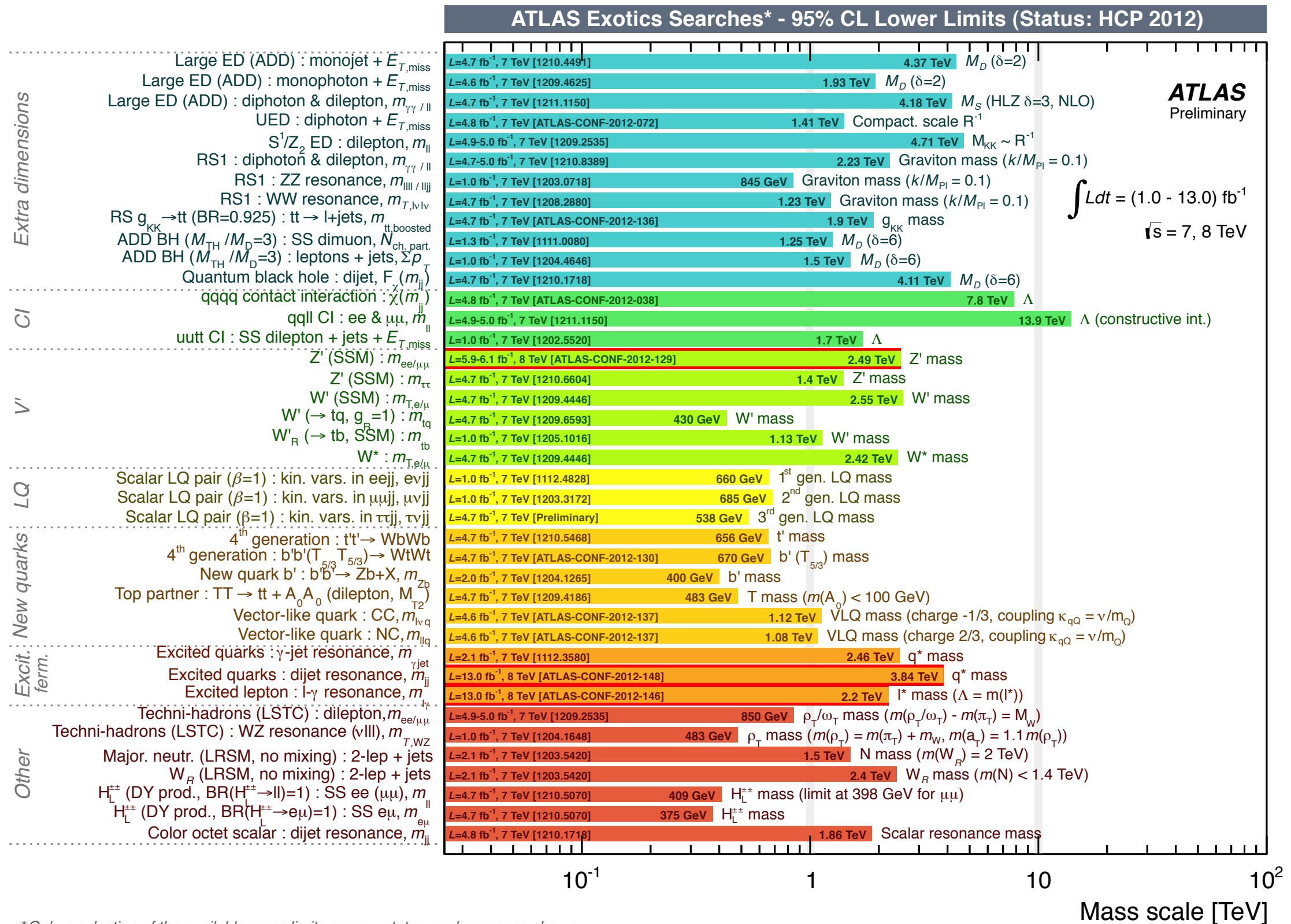
ATLAS SUSY Search

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)



*Only a selection of the available mass limits on new states or phenomena shown.
 All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

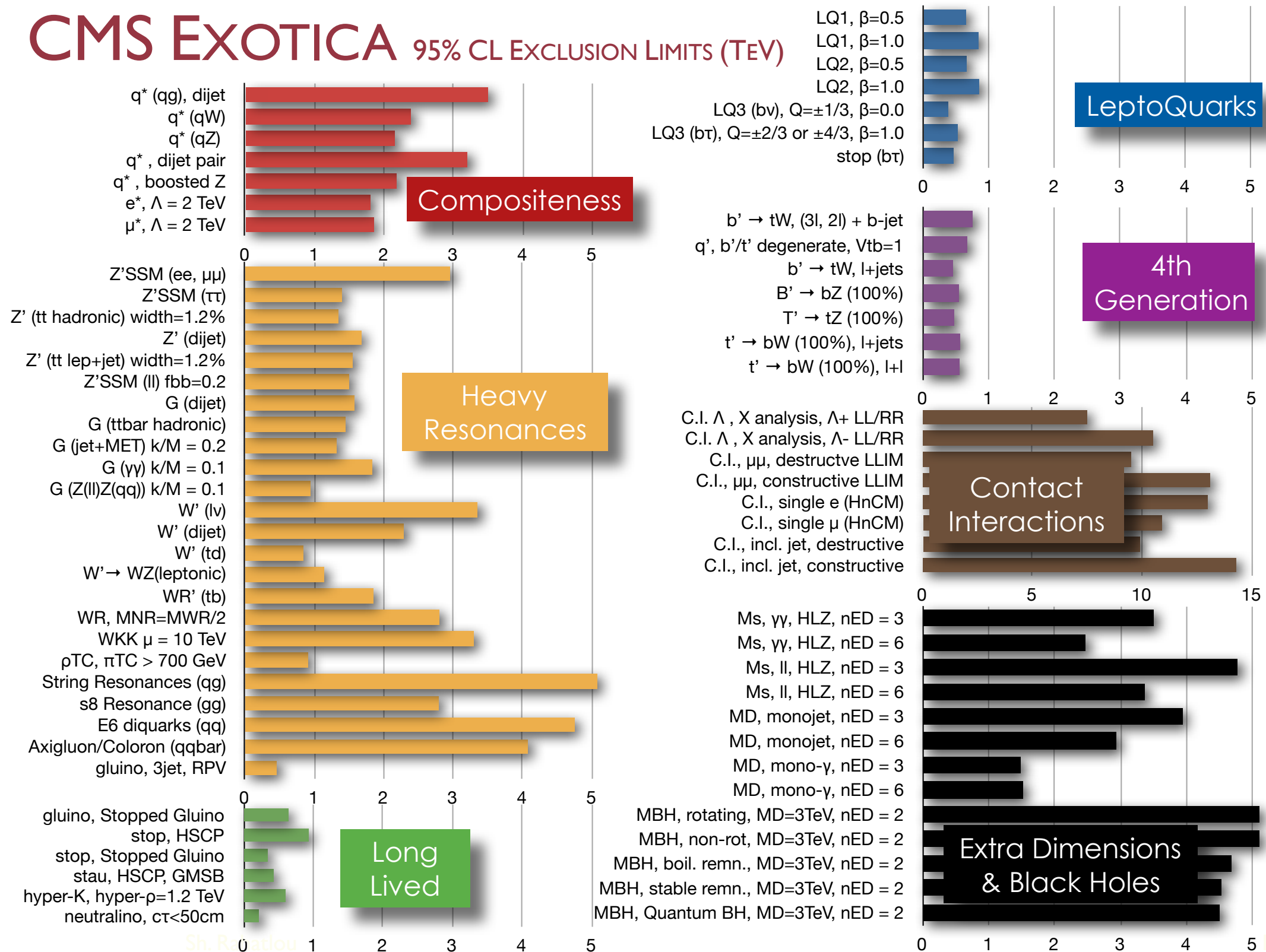
ATLAS Exotica Search



*Only a selection of the available mass limits on new states or phenomena shown

CMS Exotica Search

CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



LHC Future Prospects

- LHC ran pp at 8 TeV until end of 2012
 - ✧ 23 fb⁻¹ begins to test main Higgs properties
 - ✧ No sign of beyond-Standard-Model processes yet
- Restart late 2014 at 13 TeV
 - ✧ ~300 fb⁻¹ by 2021: Higgs properties to ~10%
 - ✧ New physics searches to multi-TeV range
- Luminosity upgrade ~2023 → 3000 fb⁻¹ by 2030?
- Energy upgrade > 2035 would need new magnets or tunnel

Conclusions and Prospects

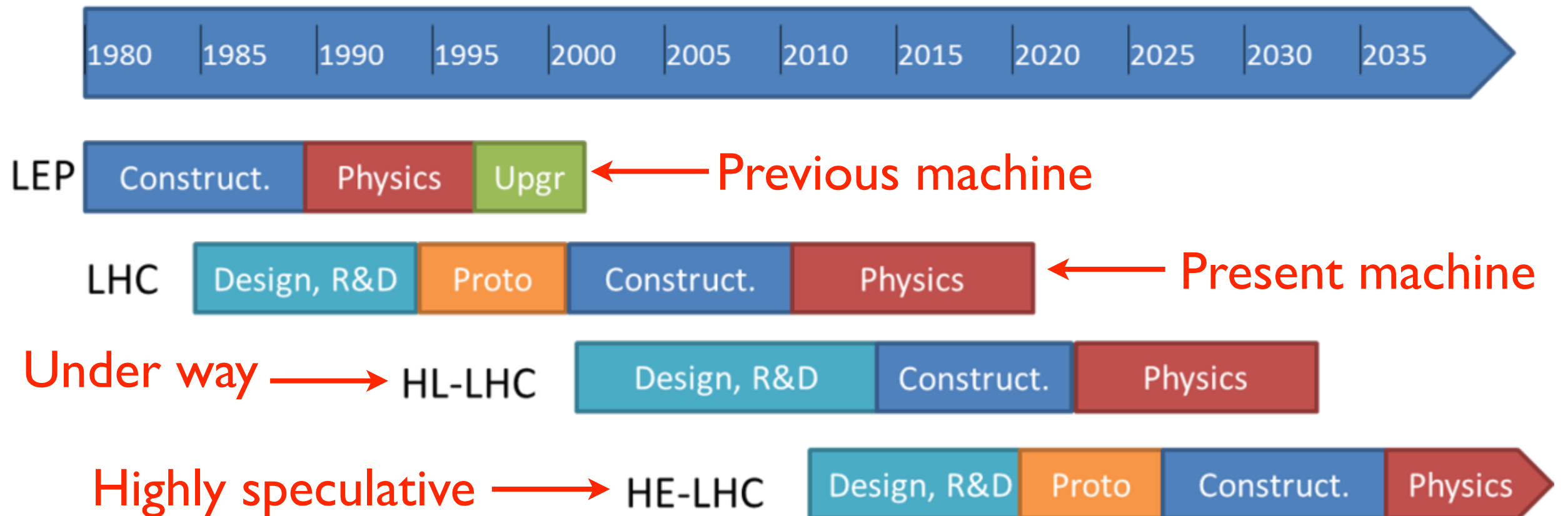
- Standard Model has (so far) been spectacularly confirmed at the LHC
- Monte Carlo event generation of (SM and BSM) signals and backgrounds plays a big part
- Matched NLO and merged multi-jet generators have proved essential
 - ✦ Automation and NLO merging in progress
 - ✦ NNLO much more challenging
- Still plenty of scope for new discoveries!

Thanks for listening!

Backup

LHC Future Prospects

The super-exploitation of the CERN complex:
Injectors, LEP/LHC tunnel, infrastructures



Brüling et al., CERN-ATS-2012-237
(submission to European Strategy
Symposium, Krakow, Sept 2012)

MC@NLO matching

S Frixione & BW, JHEP 06(2002)029

finite virtual

divergent

$$\begin{aligned} d\sigma_{\text{NLO}} &= \left[B(\Phi_B) + V(\Phi_B) - \int \sum_i C_i(\Phi_B, \Phi_R) d\Phi_R \right] d\Phi_B + R(\Phi_B, \Phi_R) d\Phi_B d\Phi_R \\ &\equiv \left[B + V - \int C d\Phi_R \right] d\Phi_B + R d\Phi_B d\Phi_R \end{aligned}$$

$$\begin{aligned} d\sigma_{\text{MC}} &= B(\Phi_B) d\Phi_B \left[\Delta_{\text{MC}}(0) + \frac{R_{\text{MC}}(\Phi_B, \Phi_R)}{B(\Phi_B)} \Delta_{\text{MC}}(k_T(\Phi_B, \Phi_R)) d\Phi_R \right] \\ &\equiv B d\Phi_B [\Delta_{\text{MC}}(0) + (R_{\text{MC}}/B) \Delta_{\text{MC}}(k_T) d\Phi_R] \end{aligned}$$

$$\begin{aligned} d\sigma_{\text{MC@NLO}} &= \left[B + V + \int (R_{\text{MC}} - C) d\Phi_R \right] d\Phi_B [\Delta_{\text{MC}}(0) + (R_{\text{MC}}/B) \Delta_{\text{MC}}(k_T) d\Phi_R] \\ &\quad + (R - R_{\text{MC}}) \Delta_{\text{MC}}(k_T) d\Phi_B d\Phi_R \end{aligned}$$

finite ≥ 0

MC starting from no emission

MC starting from one emission

- Expanding gives NLO result

POWHEG matching

P Nason, JHEP 11(2004)040

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

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

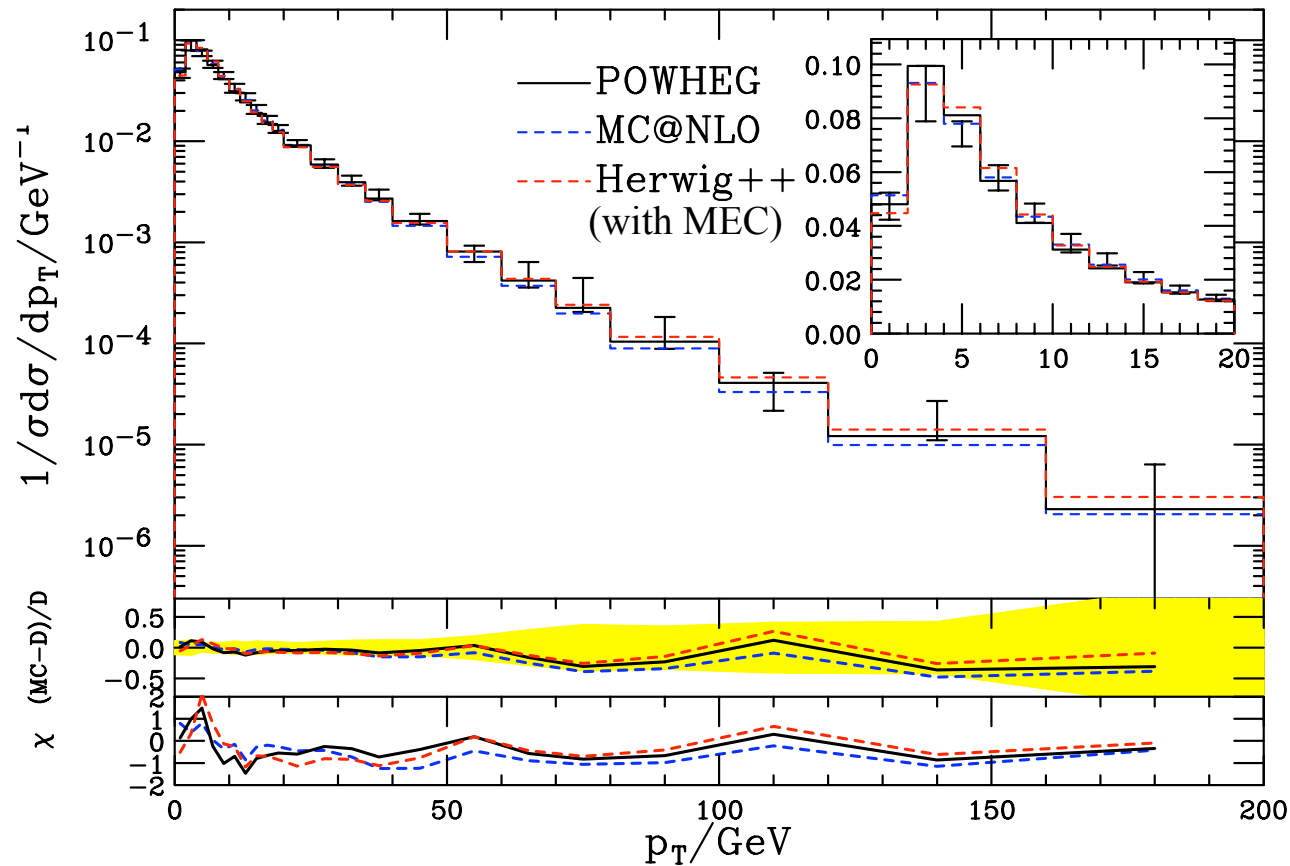
$$\bar{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int \left[R(\Phi_B, \Phi_R) - \sum_i C_i(\Phi_B, \Phi_R) \right] d\Phi_R$$

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

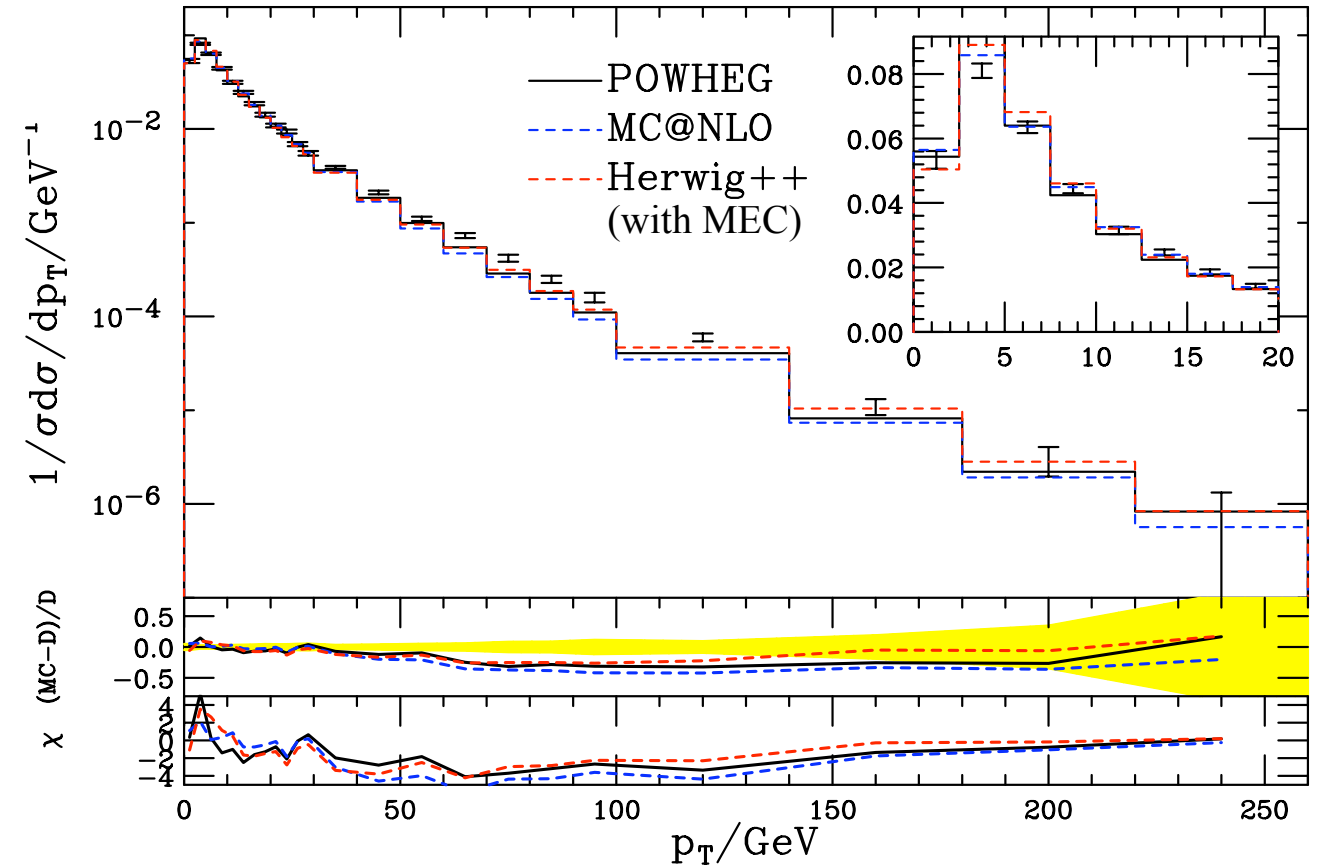
- NLO with (almost) no negative weights arbitrary NNLO
- High p_T always enhanced by $K = \bar{B}/B = 1 + \mathcal{O}(\alpha_s)$

W & Z⁰ at Tevatron

D0 Run I: W



D0 Run II: Z⁰



- Herwig++ includes W/Z+jet (MEC)
- All agree (tuned) at Tevatron
- Normalized to data

Hamilton, Richardson, Tully JHEP10(2008)015