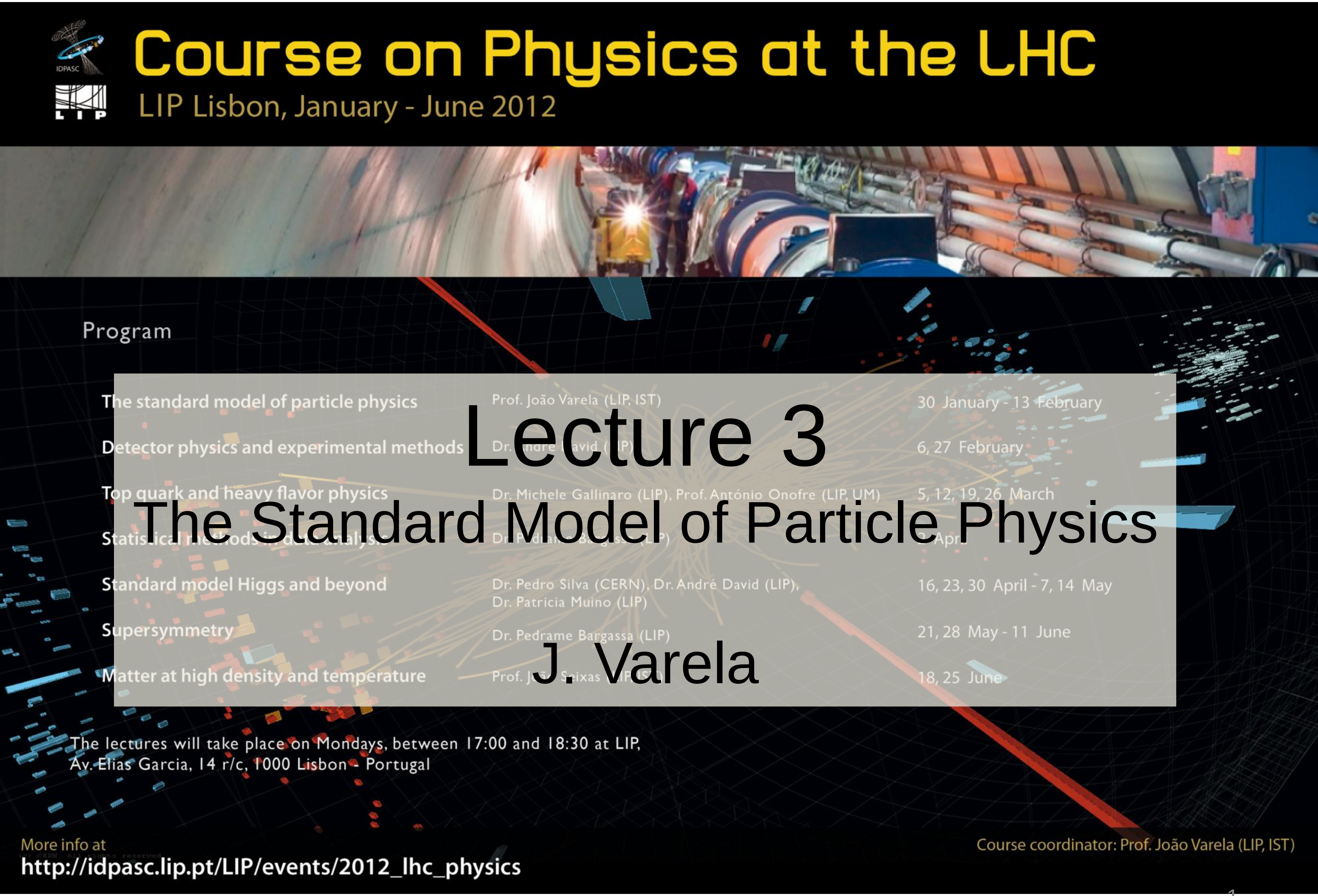
Lecture 3

The Standard Model of Particle Physics

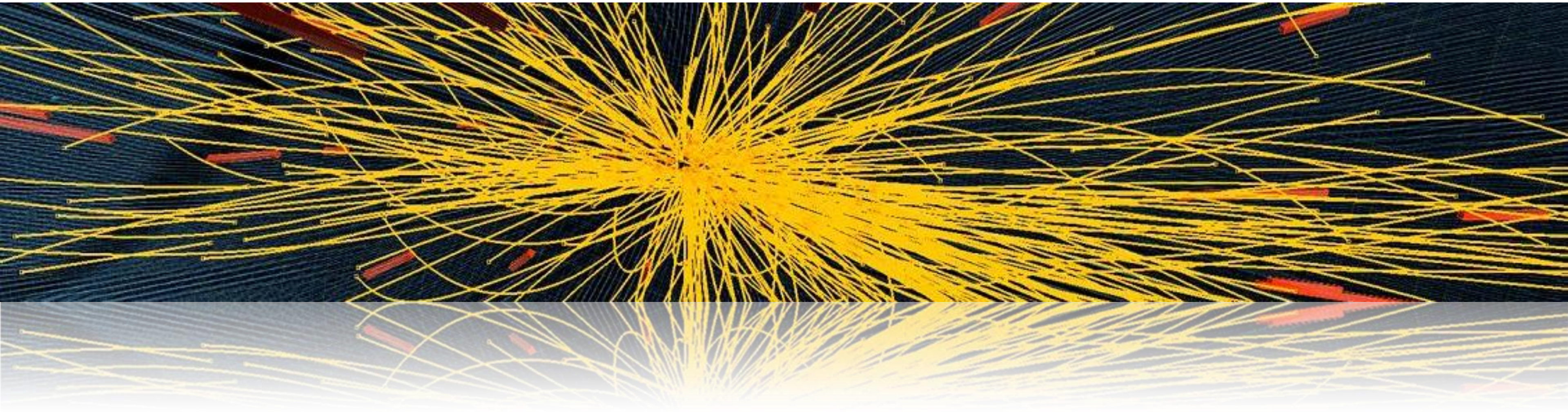
J. Varela



Lecture 3

1. Hadron interactions
2. QCD and parton densities
3. Monte Carlo generators
4. Luminosity and cross-section measurements
5. Minimum bias events
6. Jet physics
7. W and Z bosons
8. Electroweak theory (reminder)

Hadron Interactions



Natural units

$$\hbar = 1,\ c = 1$$

$$\hbar c = 197.3 \text{ MeV fm}$$
$$(\hbar c)^2 = 0.3894 \text{ GeV}^2 \text{ mb}$$

Four-vector kinematics

$$p = (E, \vec{p}\,)$$

$$p^2 = E^2 - \vec{p}^{\,2} = m^2$$

$$\beta = p/E,\ \gamma = E/m$$

Lorentz invariance

$$p_1 \cdot p_2 = E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2$$

Cross-sections should be function of scalar products of 4-vectors

4-vector scalar product Lorentz invariant

Reference frames

$$p = (E, \vec{p}\,)$$

Particle momentum as seen
in laboratory frame ...

$$p^* = (E^*, \vec{p}^{\,*})$$

Particle momentum as viewed from a
frame moving with velocity β_f ...

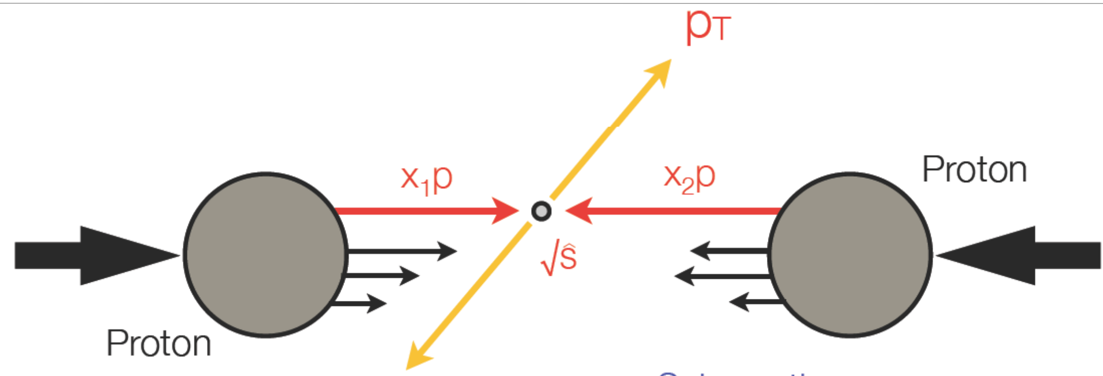
Lorentz transformation

Lorentz Transformation:

$$E^* = \gamma_f \cdot E - \gamma_f \beta_f \cdot p_{||}$$
$$p^*_{||} = \gamma_f \cdot p_{||} - \gamma_f \beta_f \cdot E$$
$$p^*_T = p_T$$

with $\gamma_f = (1 - \beta_f^2)^{-\frac{1}{2}}$

Kinematical variables

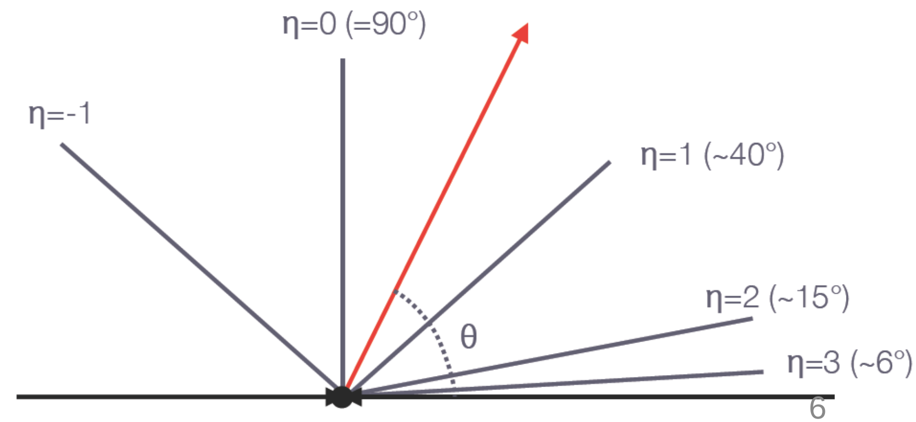


Schematic
proton-proton scattering

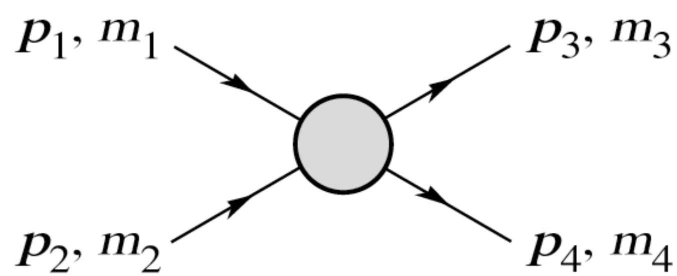
Relevant kinematic variables:

- Transverse momentum: p_T
- Rapidity: $y = ½ \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan ½\theta$
- Azimuthal angle: φ

Pseudorapidity



Invariant mass



Invariant Mass:

$$M^2 = (p_1 + p_2)^2$$
$$= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$
$$= m_1^2 + m_2^2 + 2E_1E_2(1 - \vec{\beta}_1\vec{\beta}_2)$$

Center of mass energy

Center-of-mass Energy:

$$E_{\mathrm{cm}} = \left[(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2\right]^{\frac{1}{2}}$$

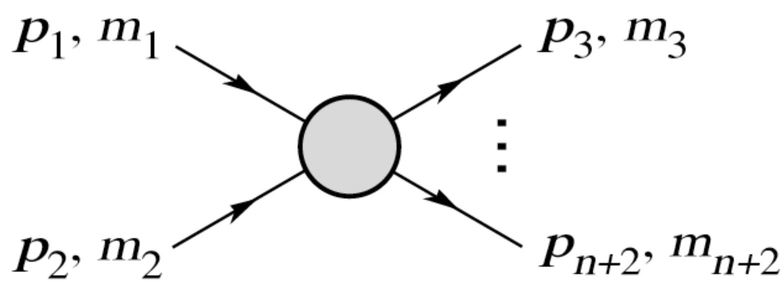
Particle 2 at rest:

$$\sqrt{s} = \quad E_{\mathrm{cm}} = \left[m_1^2 + m_2^2 + 2E_1m_2\right]^{\frac{1}{2}}$$

Particle Collider:
$[E_1 = E_2;\ \vec{p}_1 = -\vec{p}_2;\ m_1 = m_2 \approx 0]$

$$E_{\mathrm{cm}} = 2E$$

Cross section
Matrix element
Phase space



Differential
Cross Section:

Matrix element

$$d\sigma = \frac{(2\pi)^4 |\mathscr{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}}$$

$$\times \;\; d\Phi_n(p_1 + p_2;\; p_3, \ldots, p_{n+2})$$

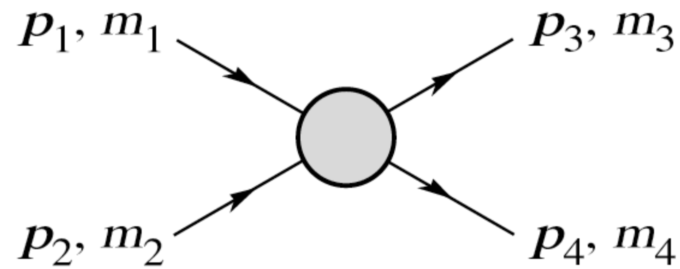
n-body
phase space

$$d\Phi_n = \ldots$$

$$\ldots = \delta^4\left(P - \sum_{i=1}^{n} p_i\right) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

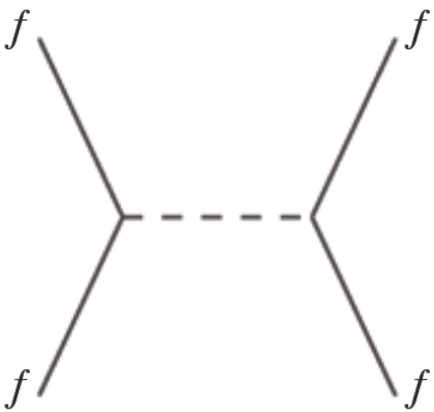
with $P = p_1 + p_2$

Mandelstam variables
Feynman diagrams



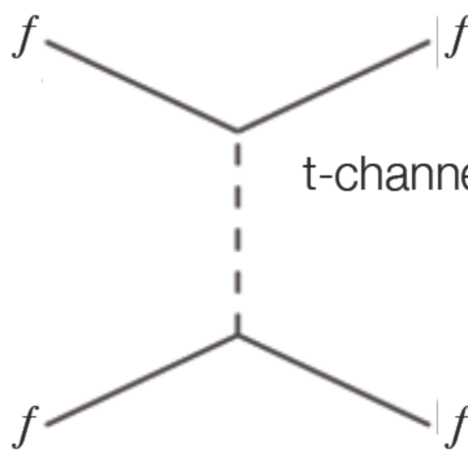
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

s-channel



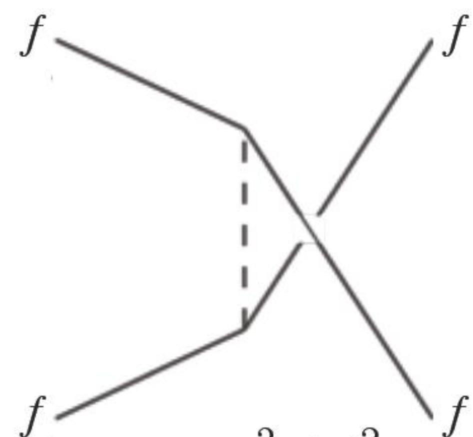
$$\sigma \propto \frac{t^2 + u^2}{s^2}$$

t-channel



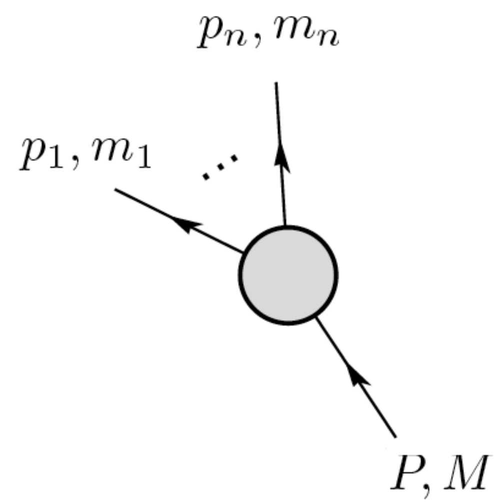
$$\sigma \propto \frac{s^2 + u^2}{t^2}$$

u-channel



$$\sigma \propto \frac{s^2 + t^2}{u^2}$$

Particle decays

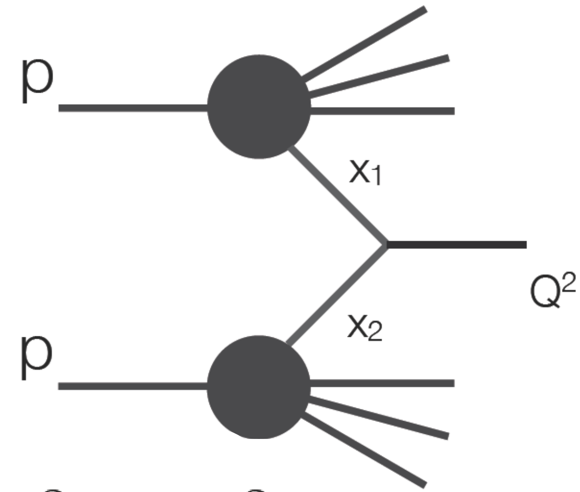


Partial
Decay Rate:

$$d\Gamma = \frac{(2\pi)^4}{2M} \, |\mathscr{M}|^2$$

$$\times \; d\Phi_n \, (P; \; p_1, \, \ldots, \, p_n)$$

Parton distributions
Bjorken-x



Proton-proton cross section

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \; f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$

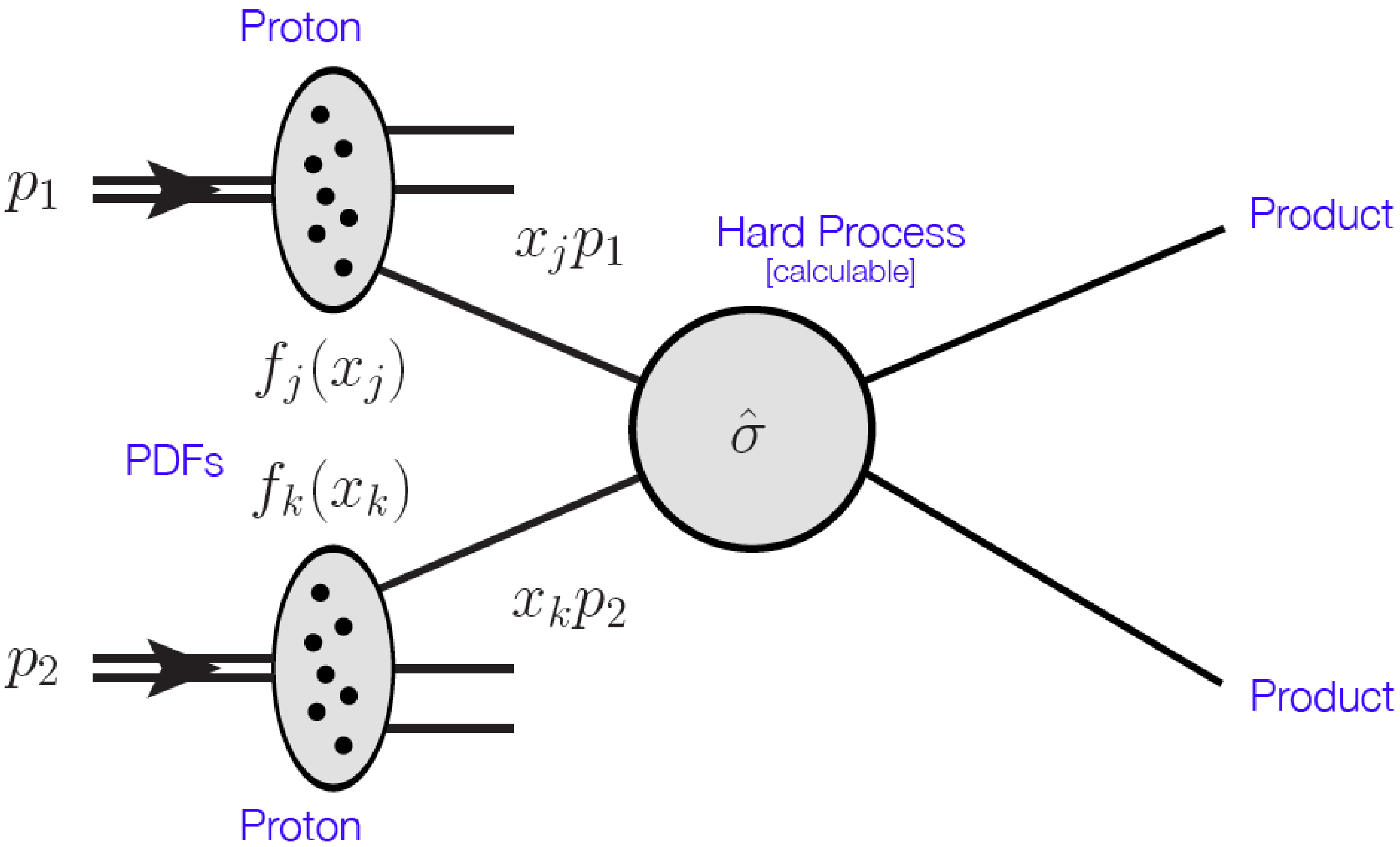
$x_{1,2}$: Bjorken-x
fractional momentum of parton
involve in hard process

Q^2 : scale; spacial resolution
invariant parton-parton mass

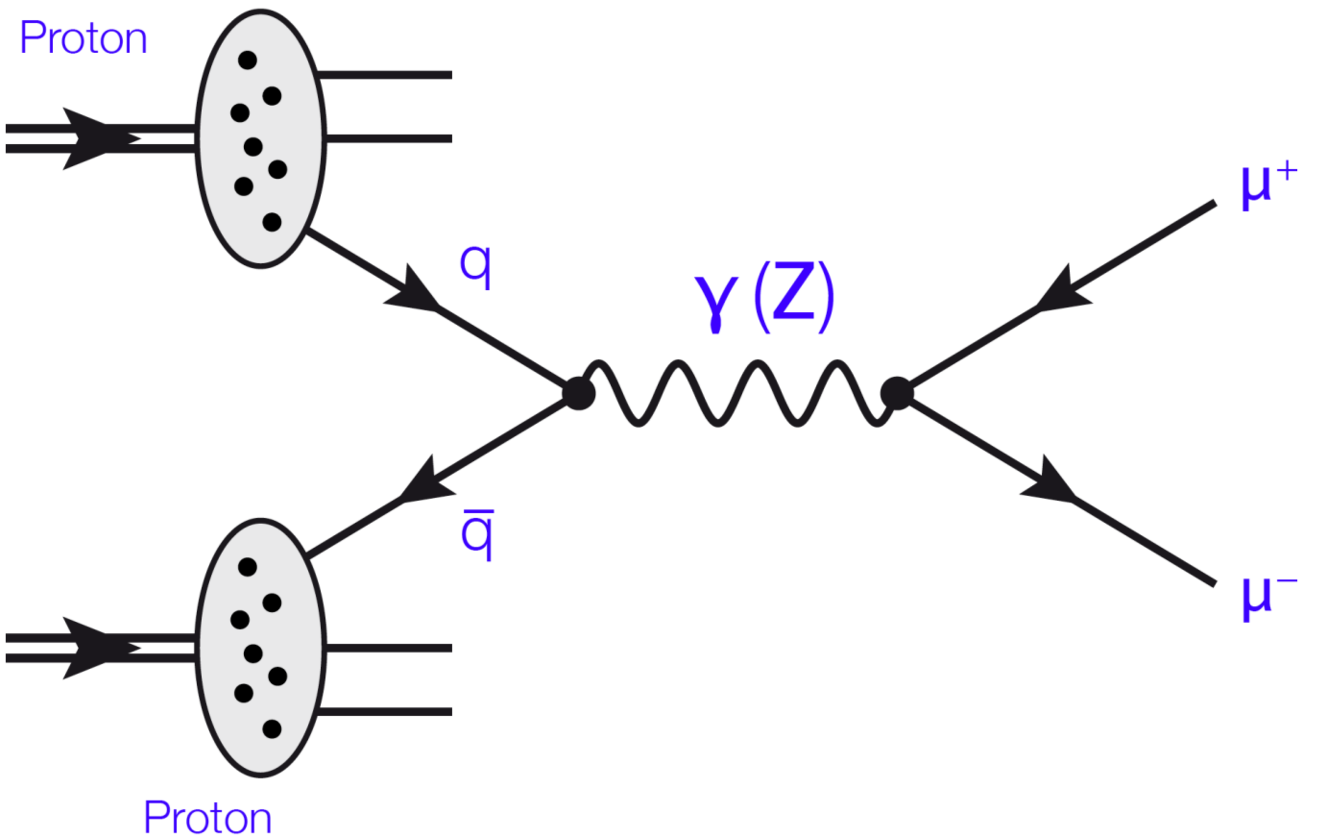
f : Parton Distribution function

Parton content:
$f(x,Q^2) = q(x,Q^2)$ or $g(x,Q^2)$

Proton-proton scattering

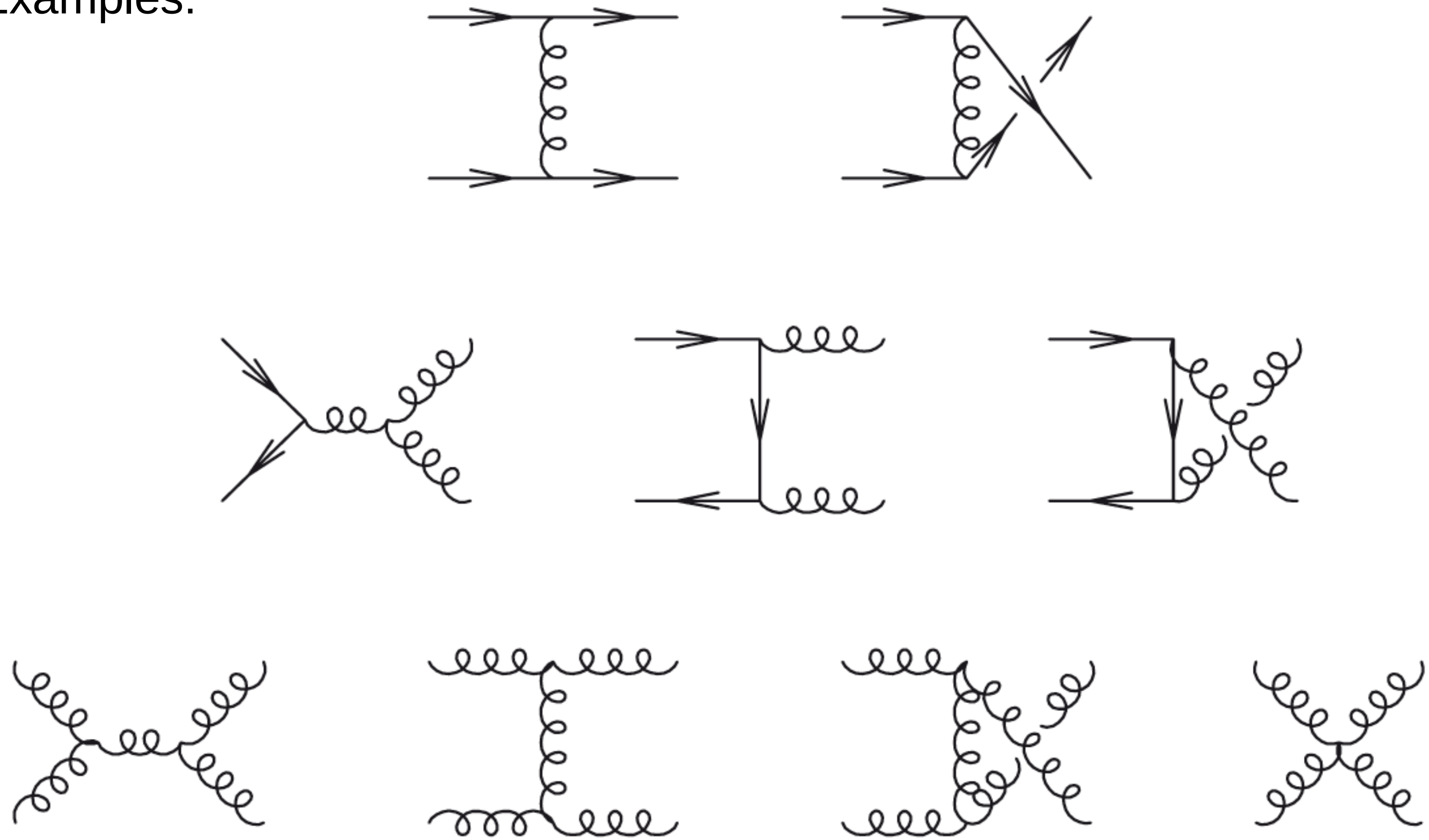


Example: Drell-Yan Process

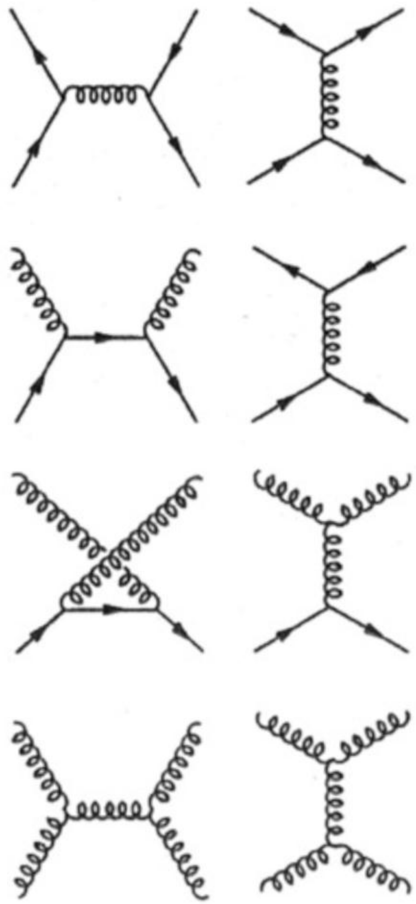


Hard processes with quarks and gluons

Examples:



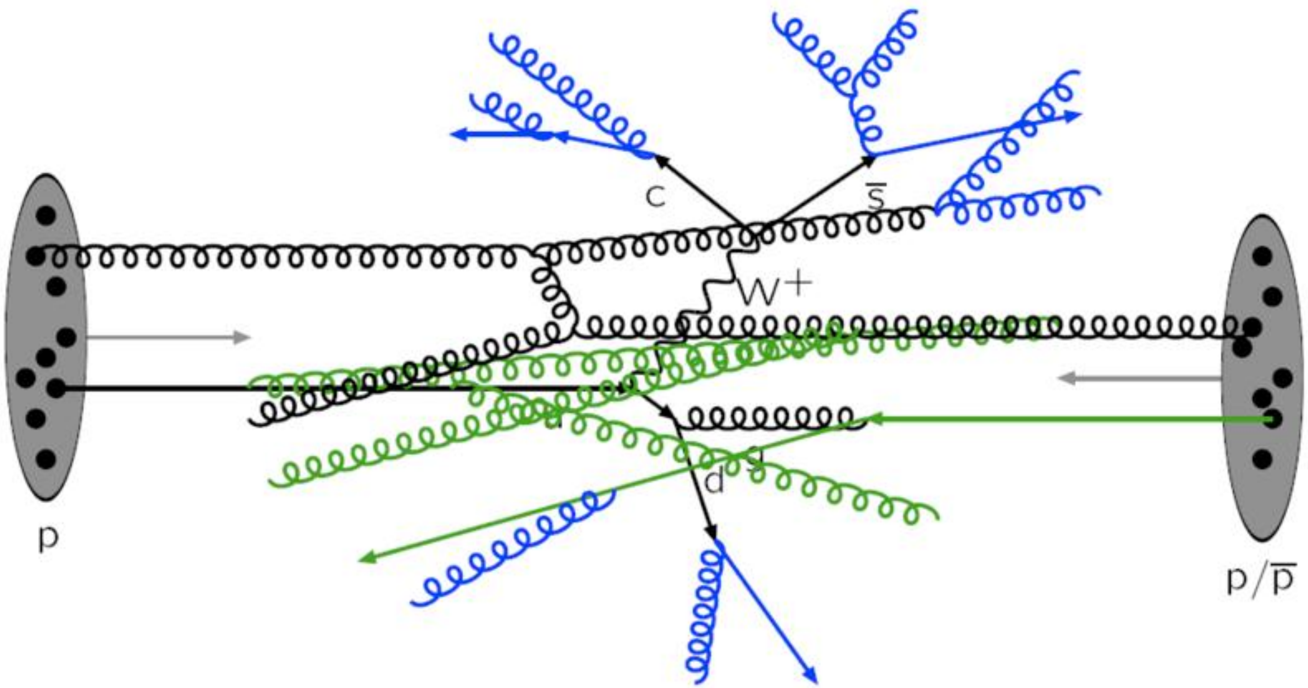
QCD Matrix Elements



Subprocess	$\lvert\mathcal{M}\rvert^2/g_s^4$	$\lvert\mathcal{M}(90^\circ)\rvert^2/g_s^4$
$\left.\begin{array}{l} qq' \to qq' \\ q\bar{q}' \to q\bar{q}' \end{array}\right\}$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.2
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{8}{3}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	1.0
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{3}{8}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	0.1
$qg \to qg$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}+3\right)$	30.4

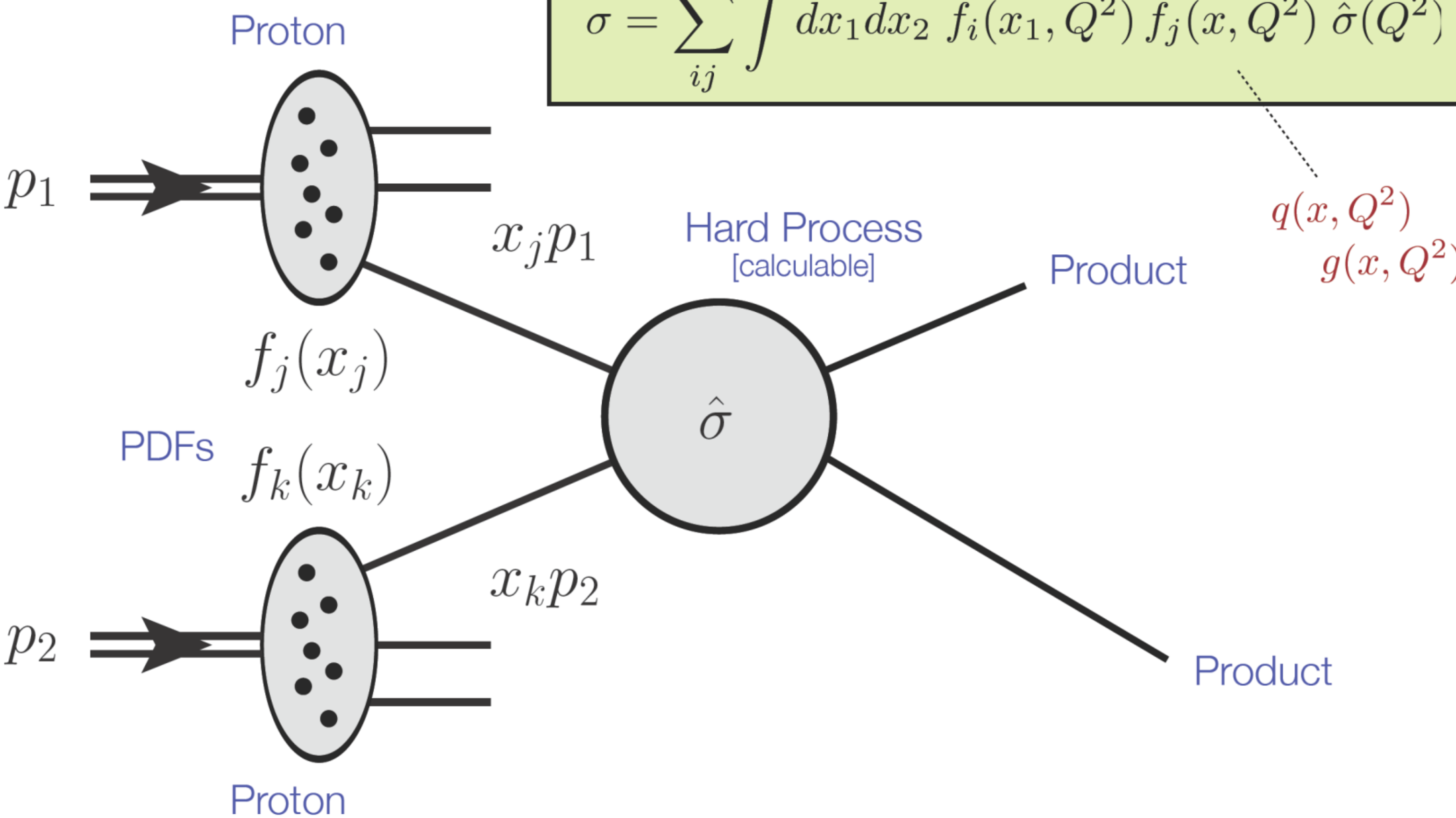
Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



Proton-Proton Scattering @ LHC

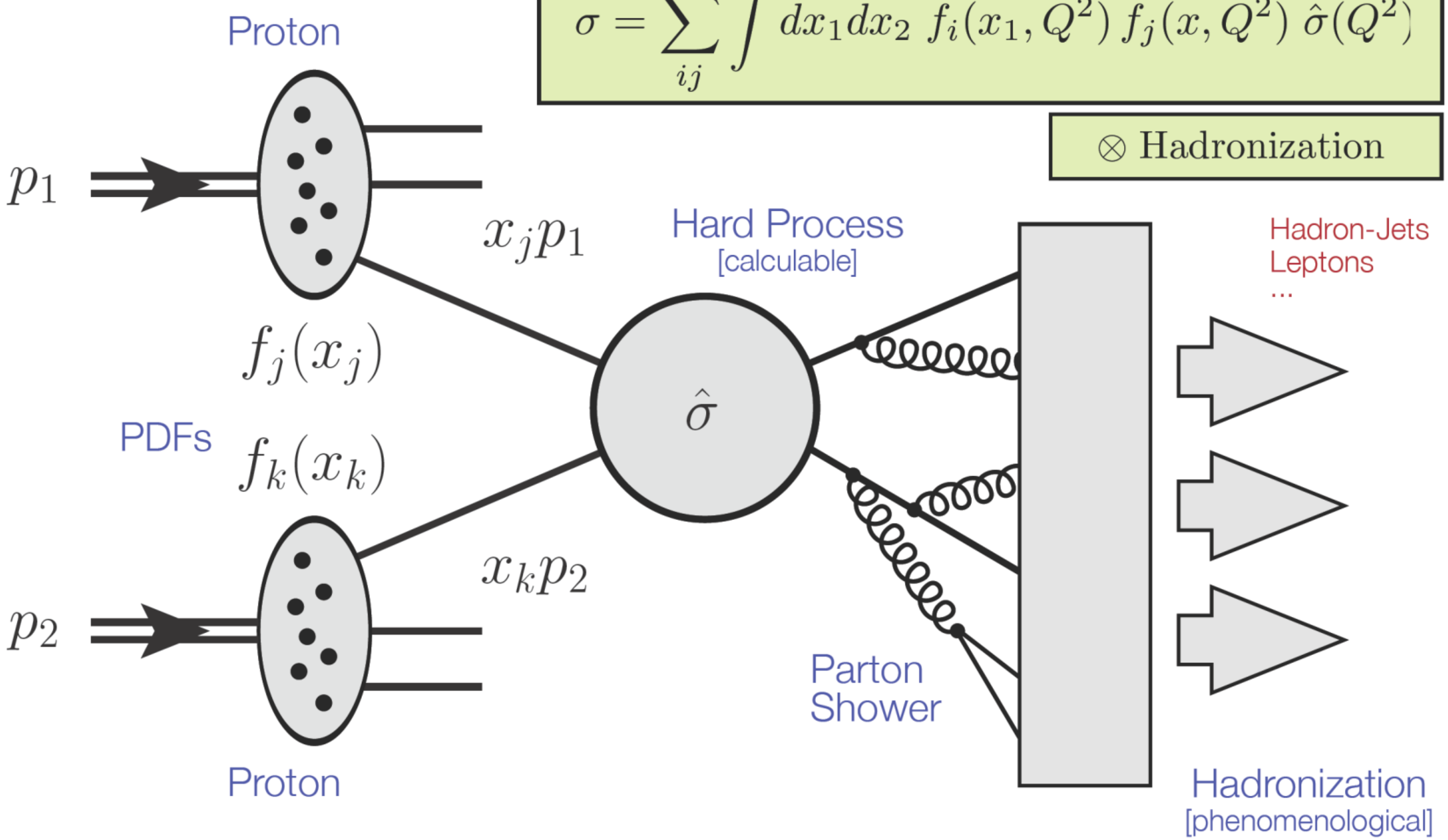
$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$



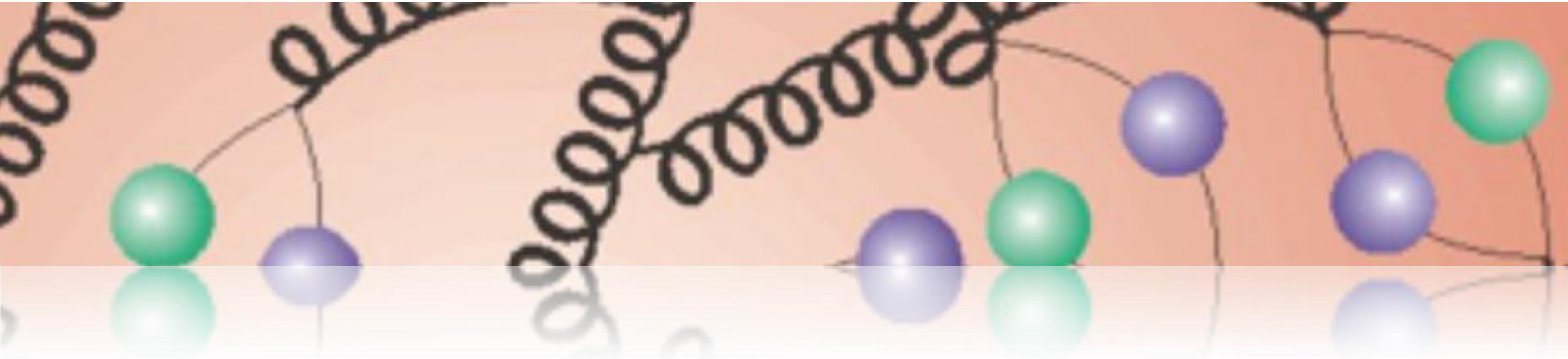
Proton-Proton Scattering @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2) \, f_j(x, Q^2) \; \hat{\sigma}(Q^2)$$

$\otimes$ Hadronization

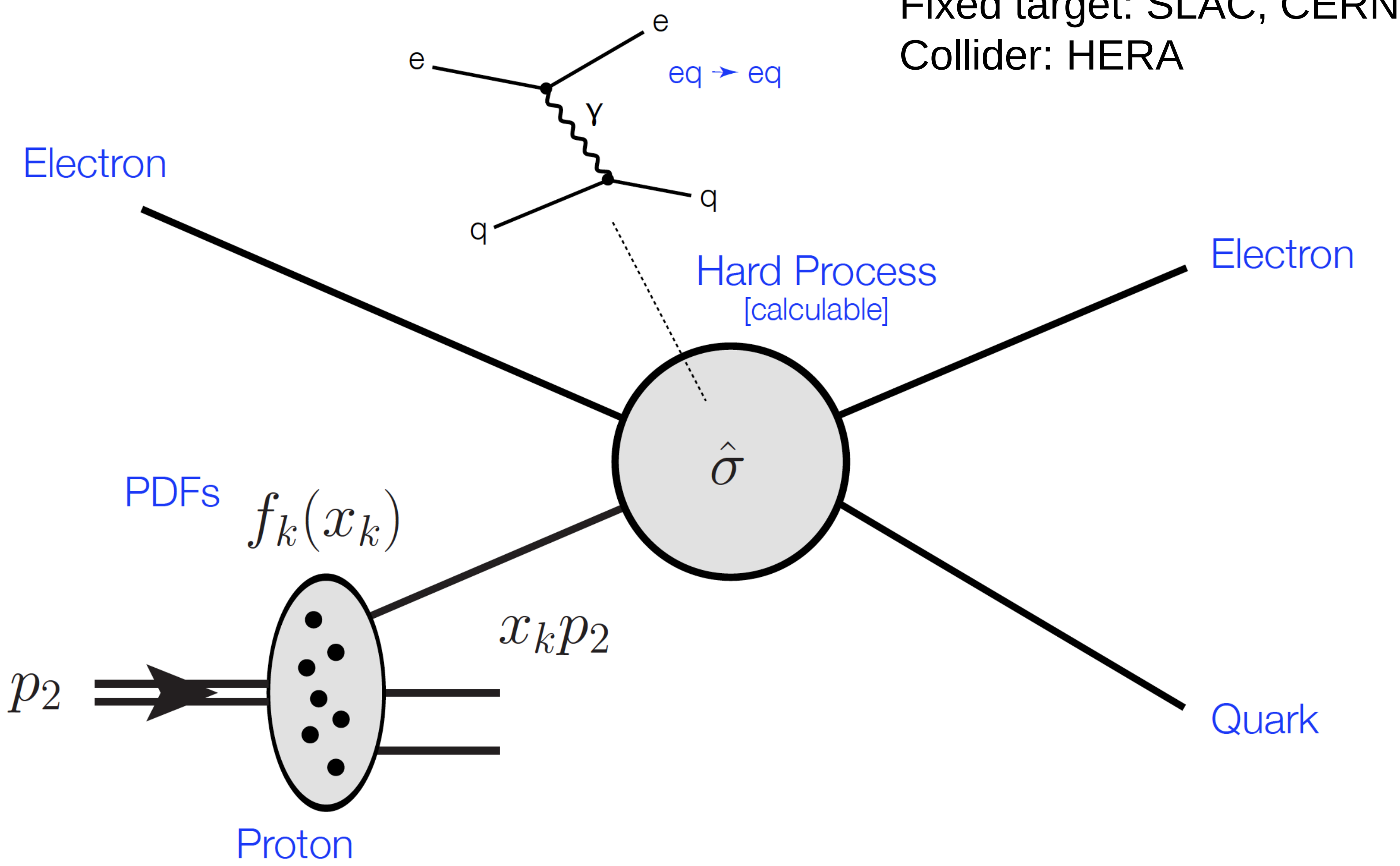


QCD & parton densities

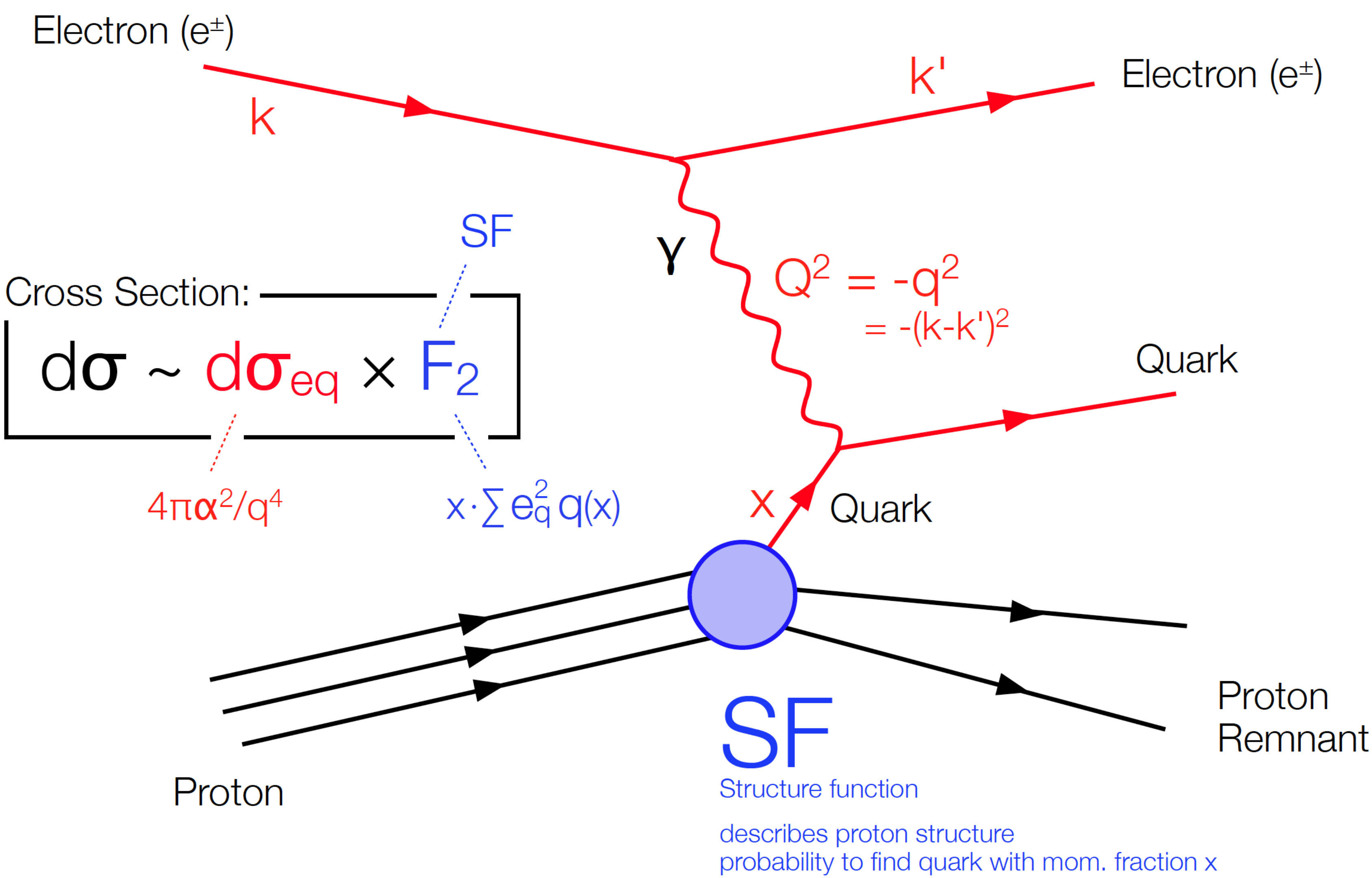


Lepton-proton scattering

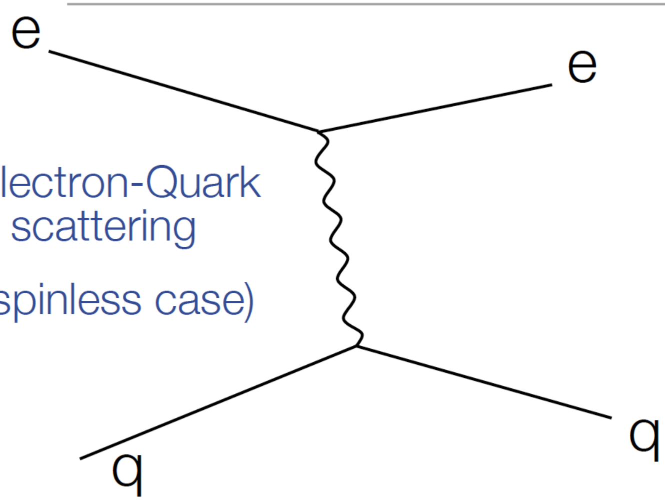
Fixed target: SLAC, CERN
Collider: HERA



Lepton-proton scattering



Structure Function F_2



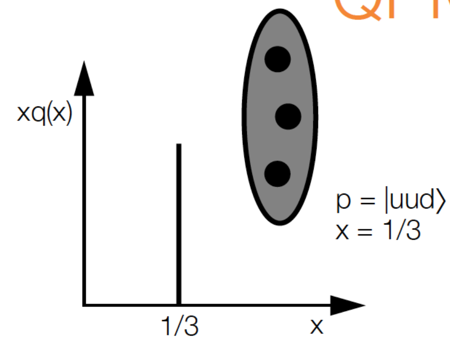
Electron-Quark scattering

(spinless case)

$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

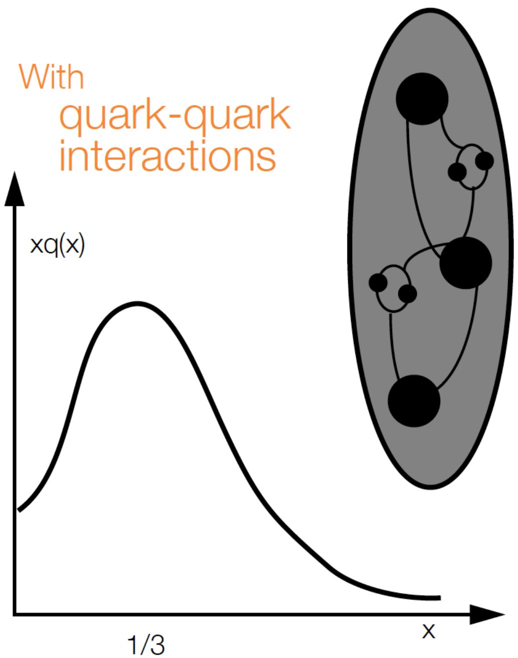
Rutherford scattering on pointlike target

Naive QPM



$$\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4}[2e_u^2 + e_d^2] = \frac{4\pi\alpha^2}{q^4}$$

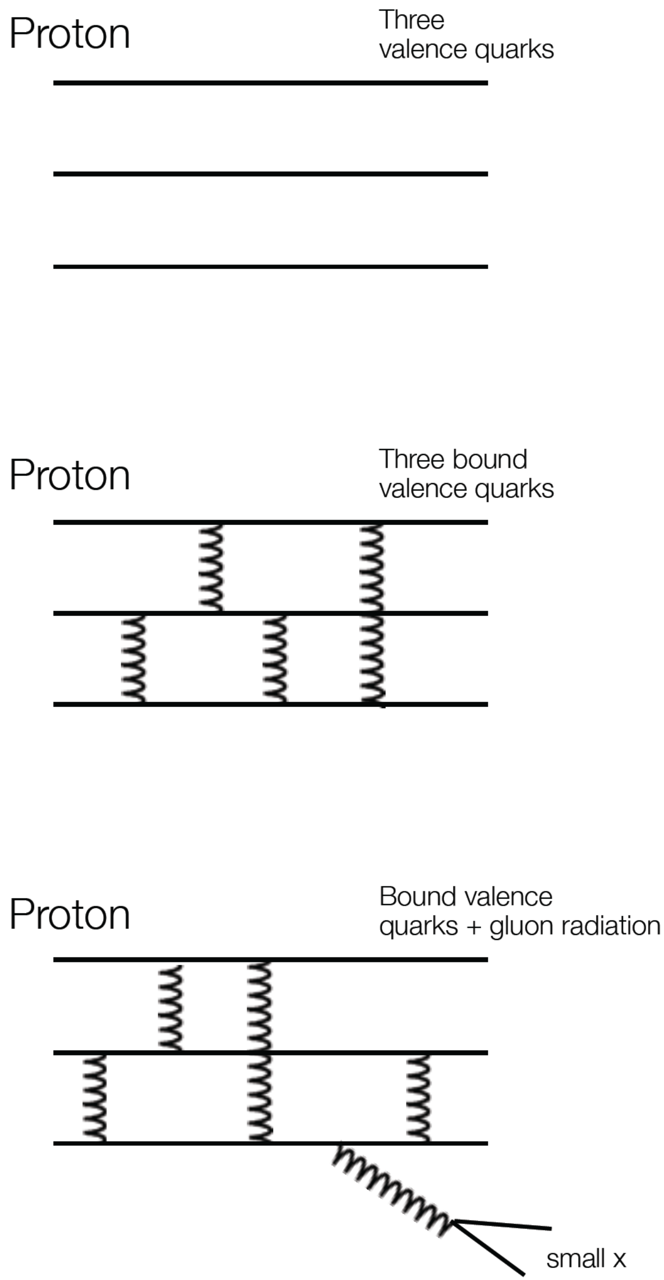
With quark-quark interactions

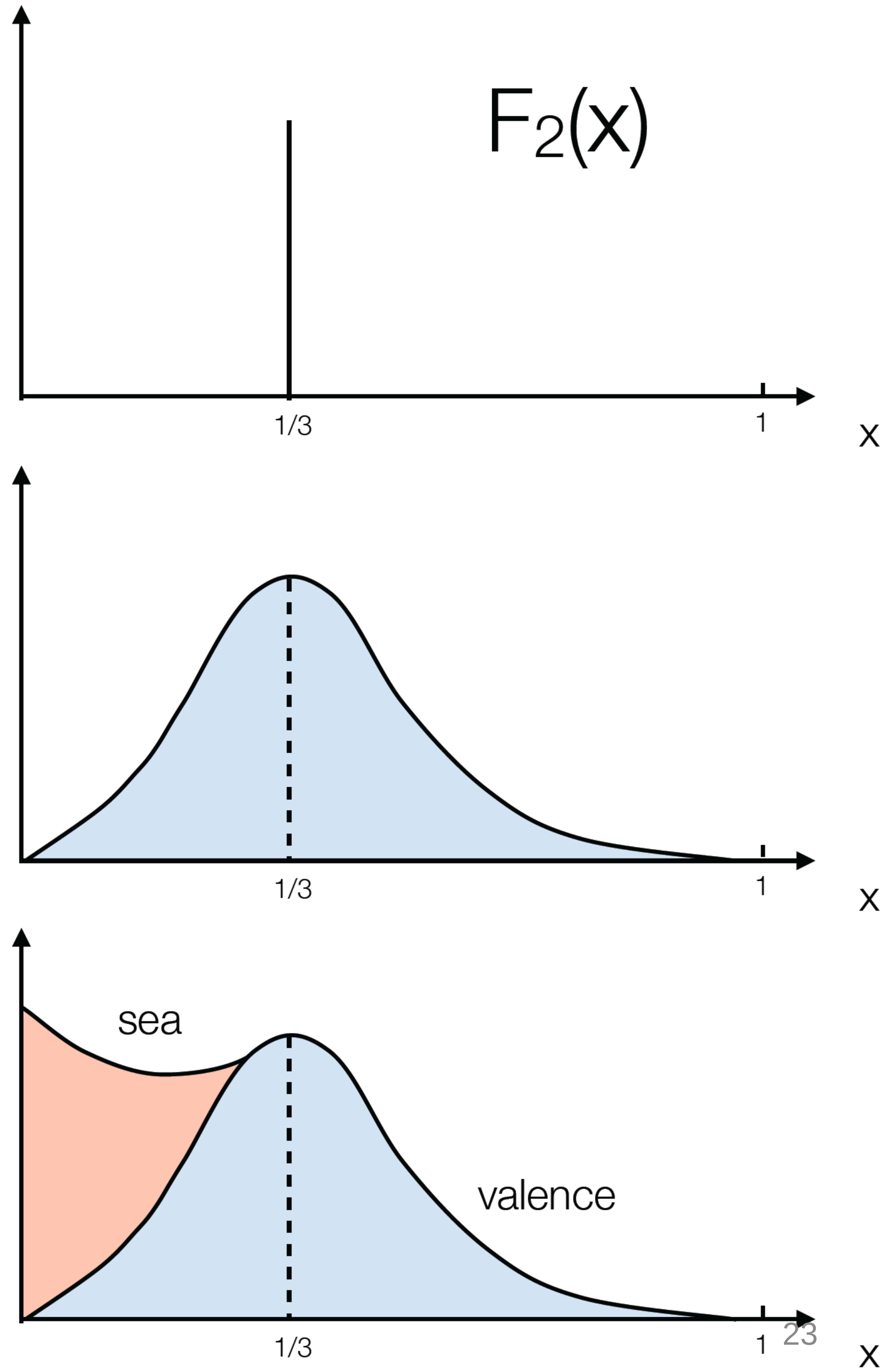


$$\frac{d\sigma(ep)}{dx\,dq^2} = \frac{4\pi\alpha^2}{q^4}[e_u^2 u(x) + e_d^2 d(x) + \ldots]$$

$$= \frac{4\pi\alpha^2}{q^4}\frac{F_2(x)}{x}$$

QPM: Structure Functions F_2 independent of Q^2

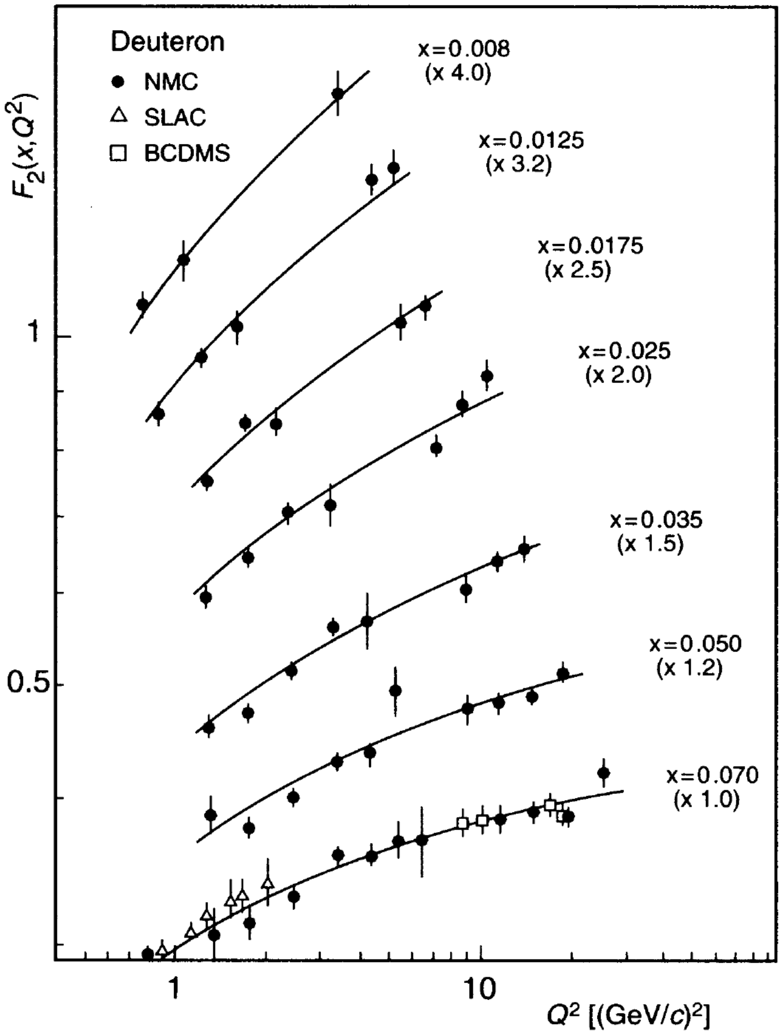


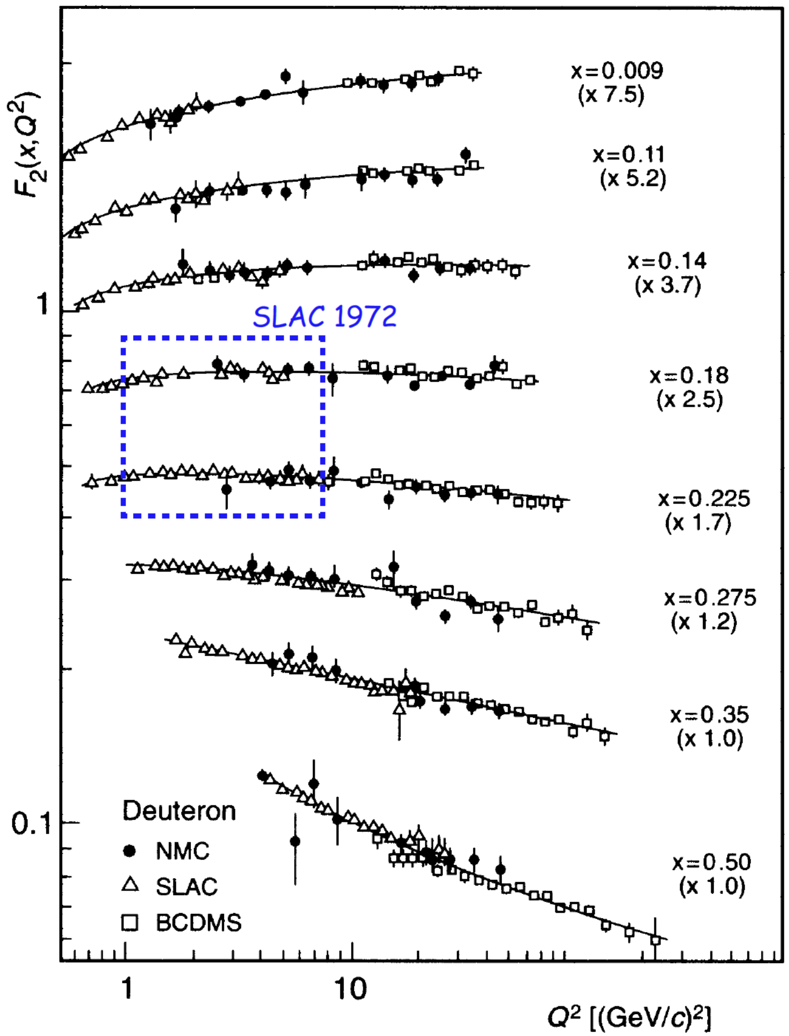


[see e.g. Halzen/Martin]

Scaling violation

$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$

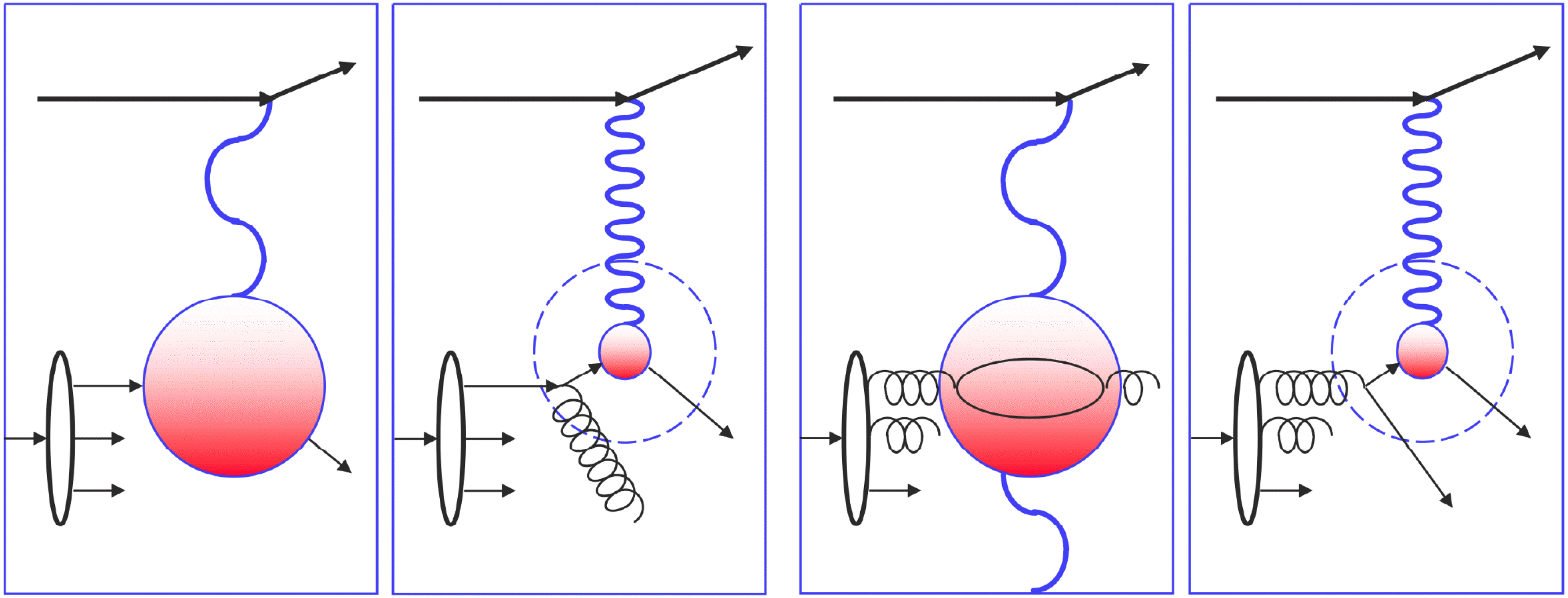




Scaling violation

Proton quark dominated:
$Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

Proton gluon dominated:
$Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x



Q^2-evolution described by DGLAP Equations

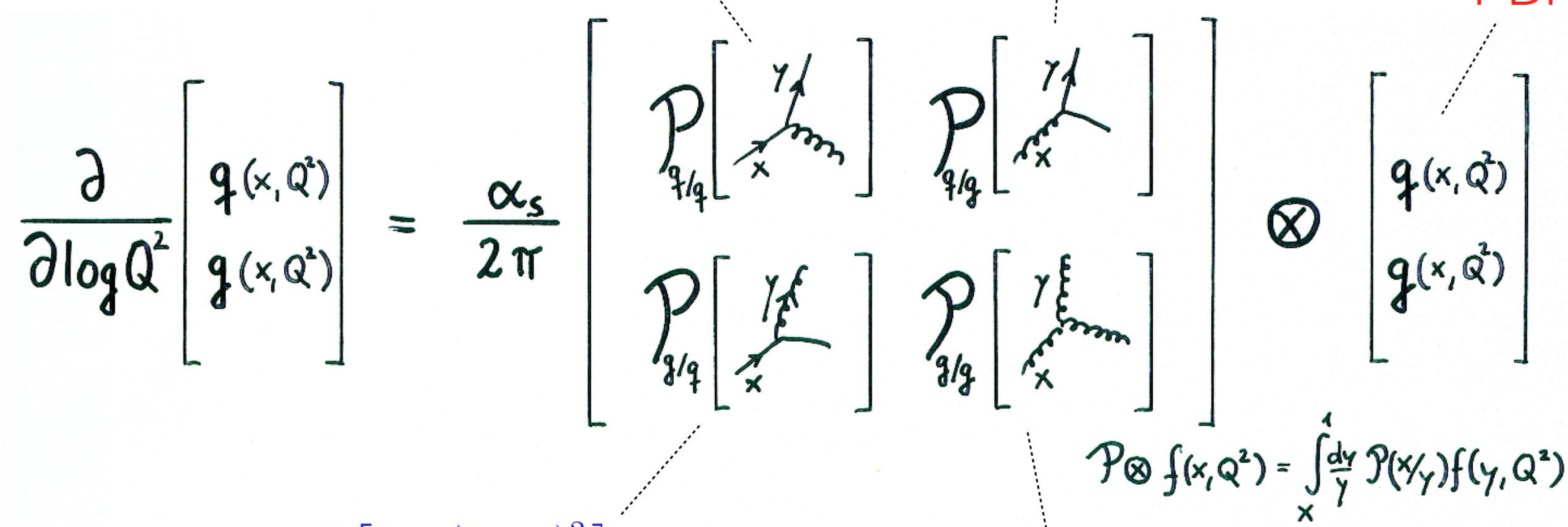
Q^2 evolution equations

[DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli, Parisi]

$$\frac{4}{3}\left[\frac{1+z^2}{1-z}\right]$$

$$\frac{1}{2}\left[z^2+(1-z^2)\right]$$

PDFs



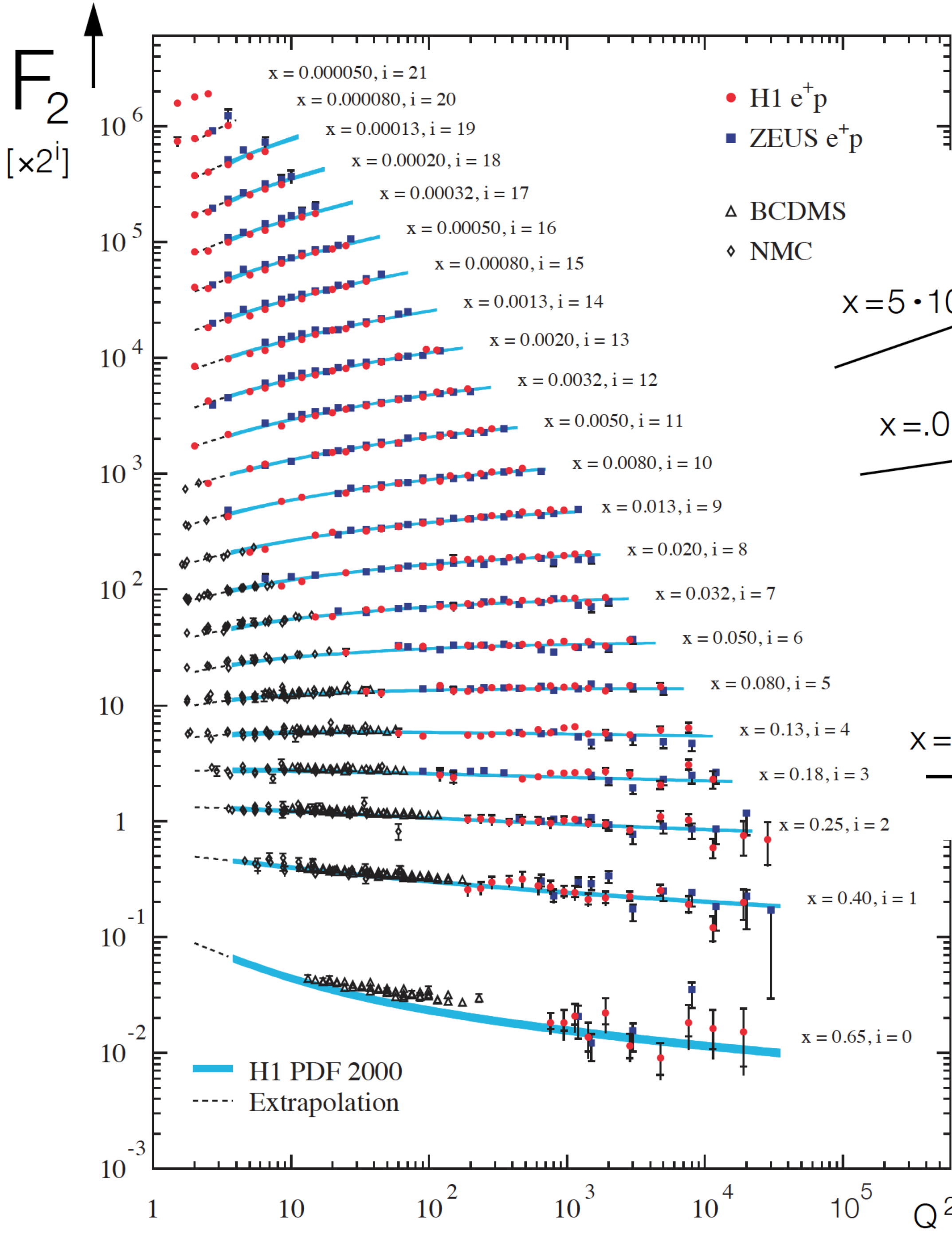
$$\frac{4}{3}\left[\frac{1+(1-z)^2}{z}\right]$$

$$6\left[\frac{z}{1-z}+\frac{1-z}{z}+z(1-z)\right]$$

[z: momentum fraction of radiated parton]

Scaling Violations

[HERA & fixed target data]



$x = 5 \cdot 10^{-3}$

$x = .013$

$x = .18$

$x = .65$

Precision: 2-3%
[bulk region]

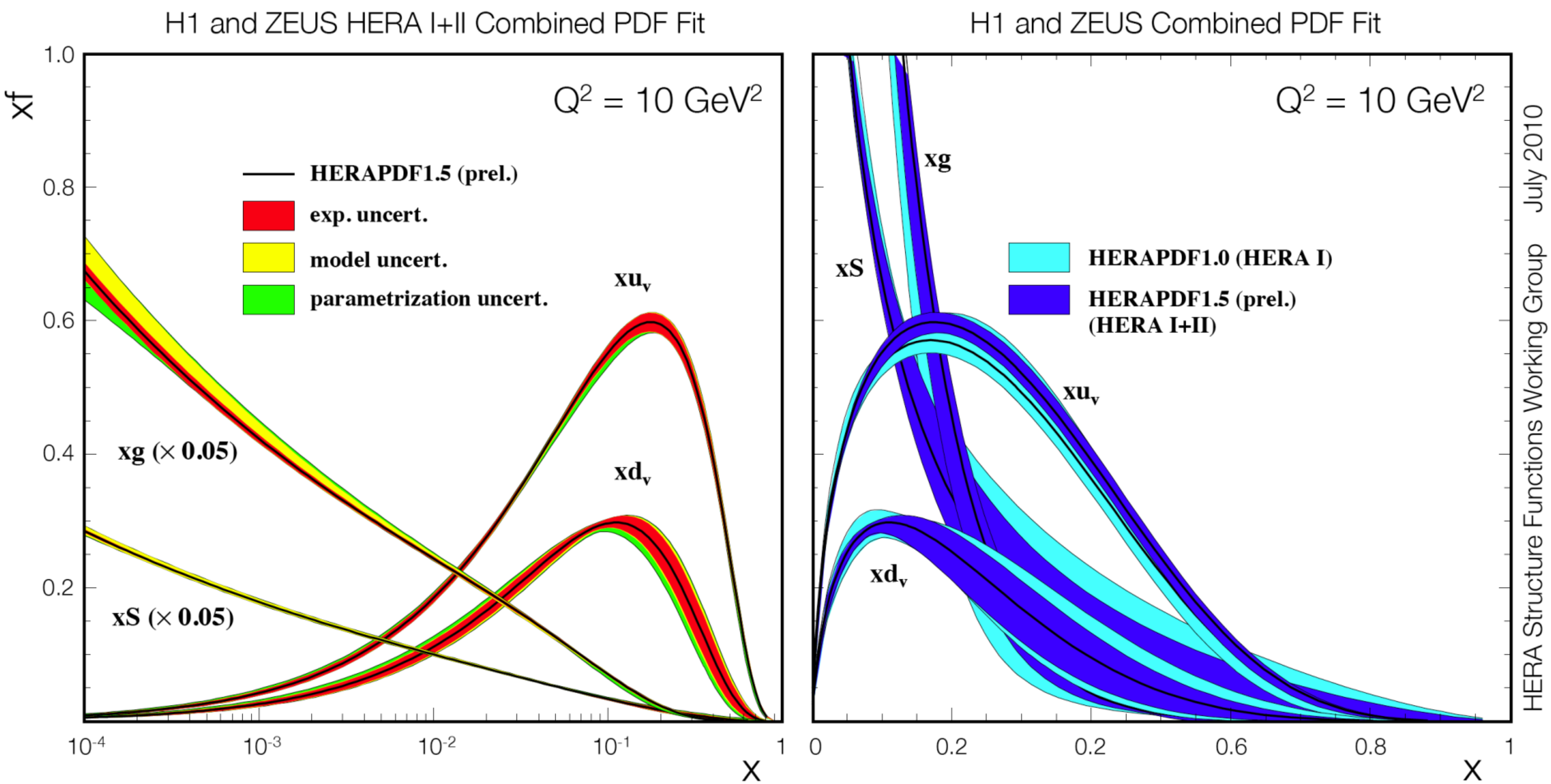
For $x < 10^{-2}$:

$$\frac{dF_2}{d\log Q^2} \sim g(x,Q^2) \cdot \alpha_s(Q^2)$$

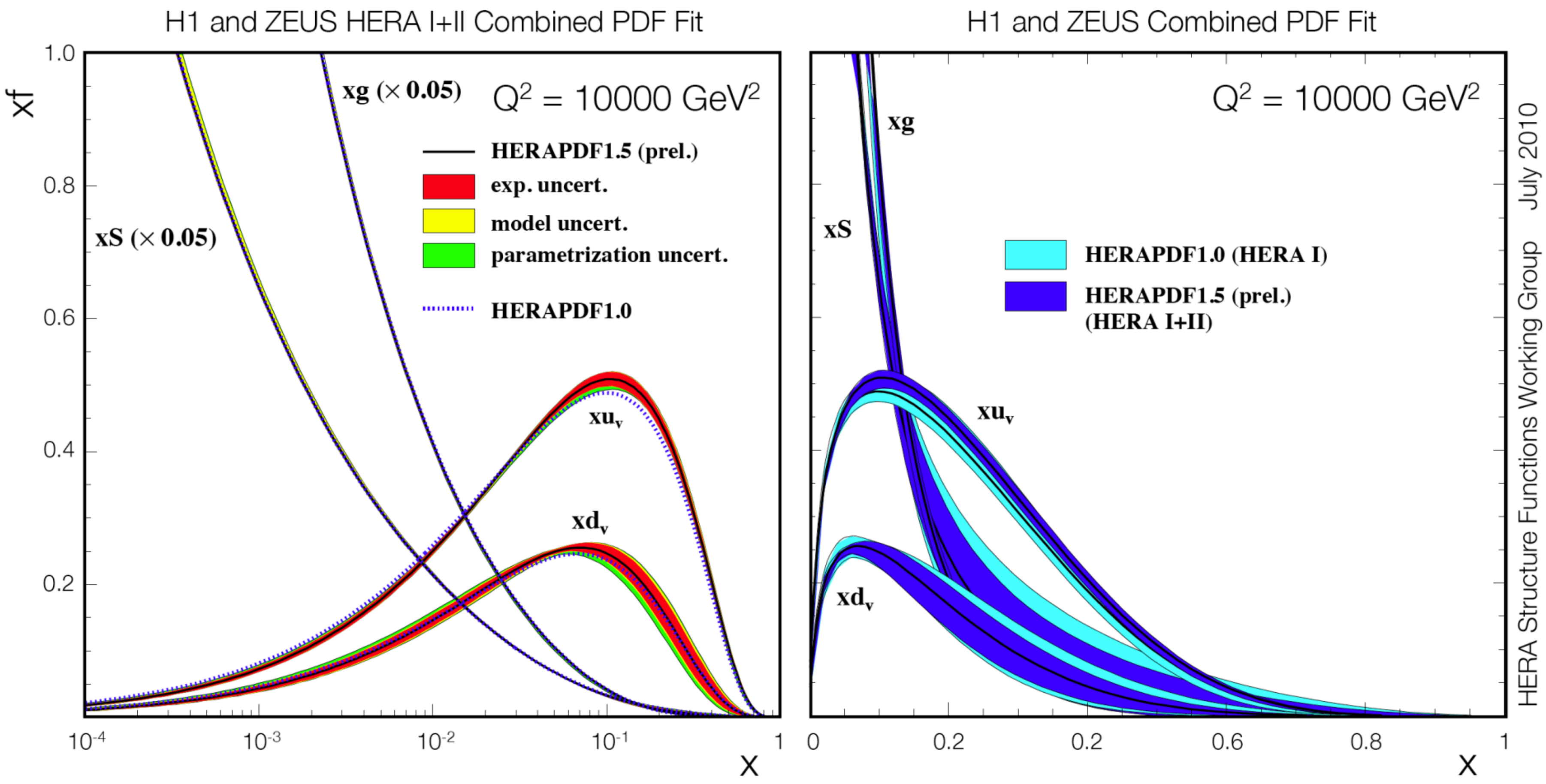
NLO QCD Fits:

Quark densities
Gluon density
Strong coupling α_s

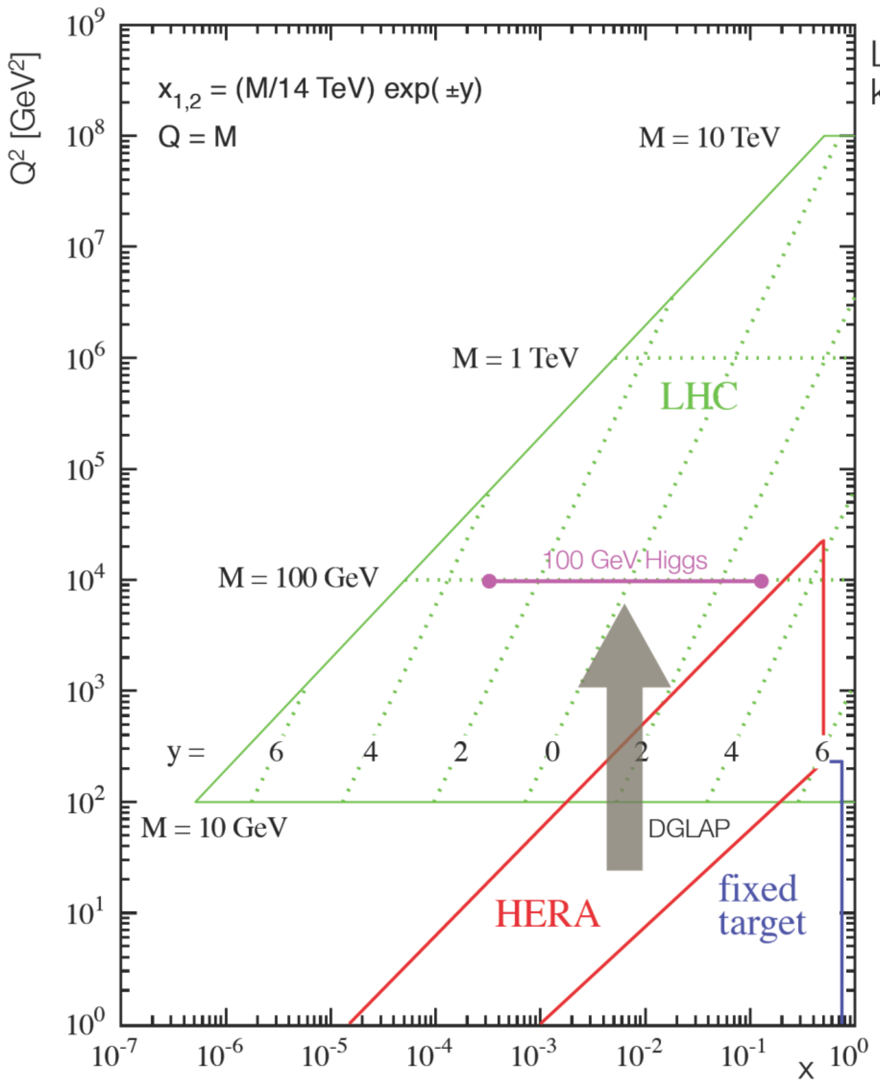
Proton parton densities



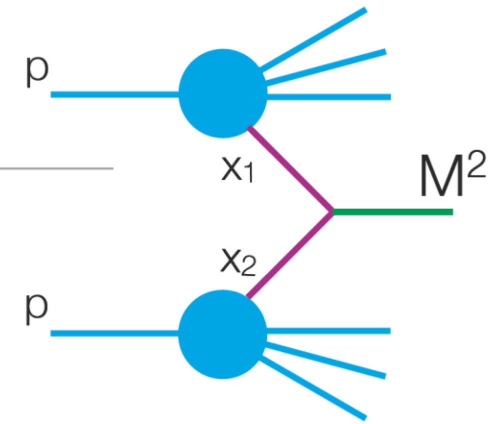
Proton parton densities



Particle production @ LHC



LHC parton kinematics



pp ➛ X_M + remnants

X_M: particle with mass M
e.g. Higgs

$M^2 = x_1 x_2 \cdot s$

i.e. to produce a particle with mass M at LHC energies ($\sqrt{s}$ = 14 TeV)

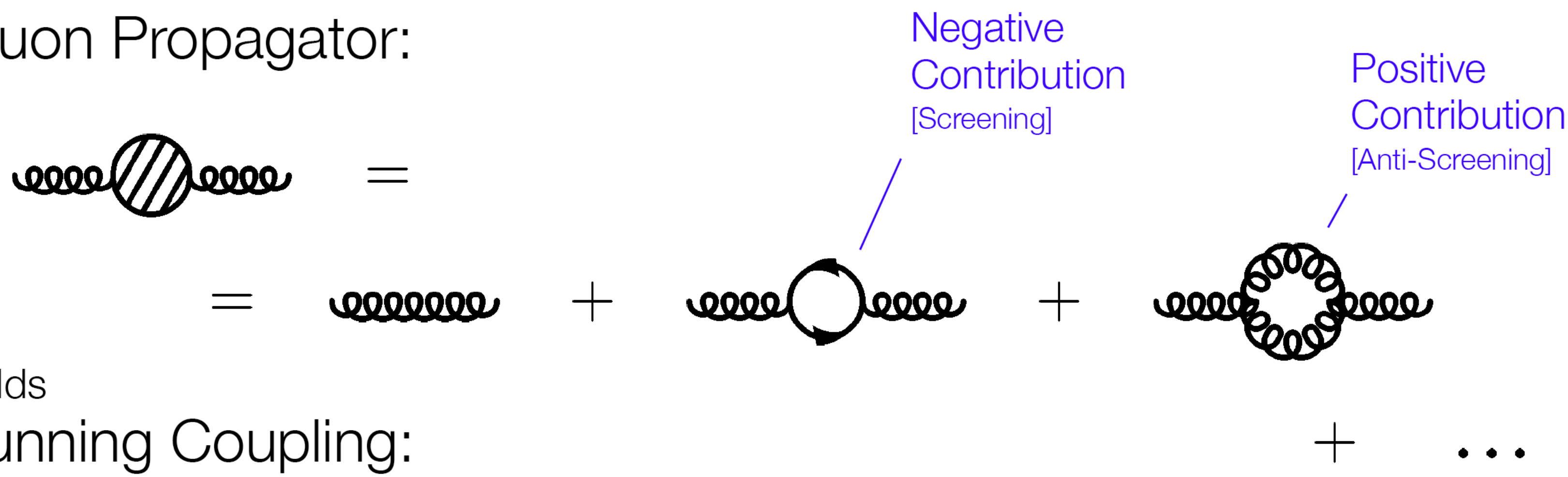
$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$
[$x_1 = x_2$: mid-rapidity]

LHC needs:

Knowledge of parton densities
Extrapolation over orders of magnitudes

Running Coupling α_s

Gluon Propagator:



Yields

Running Coupling:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \log \frac{Q^2}{\mu^2}}$$

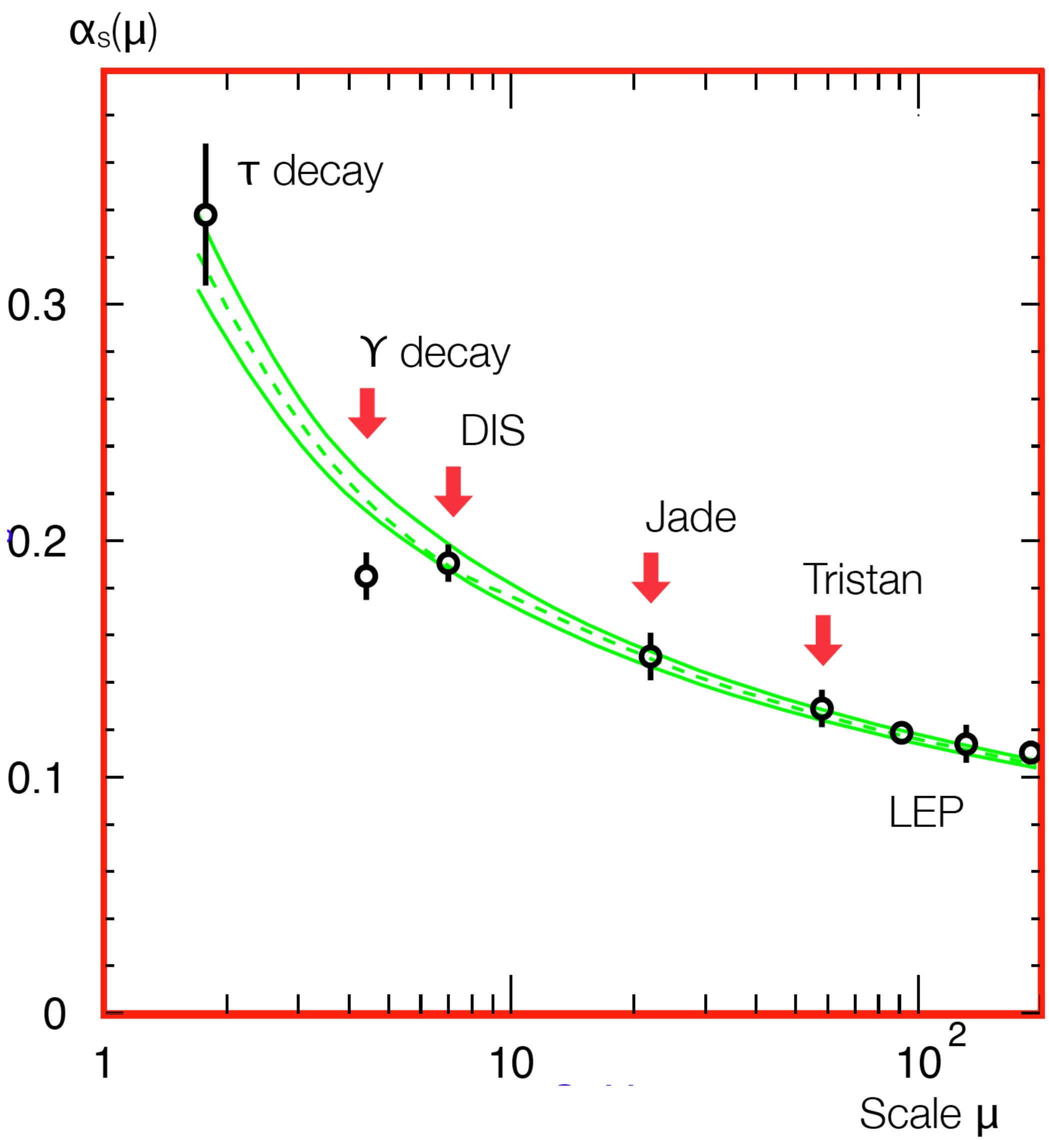
Positive Sign !

QED:

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \log \frac{Q^2}{\mu^2}}$$

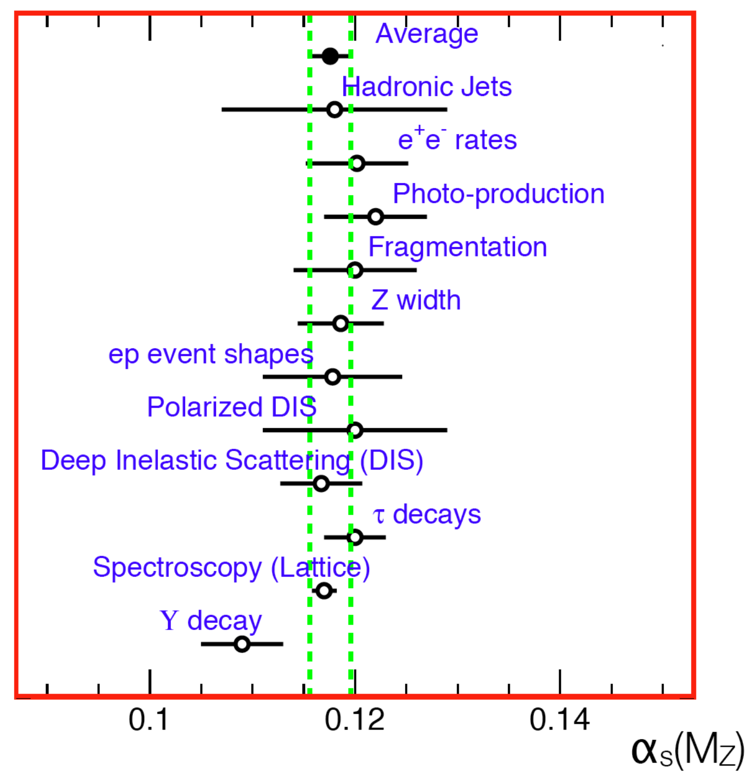
Negative Sign !

Running Coupling α_s

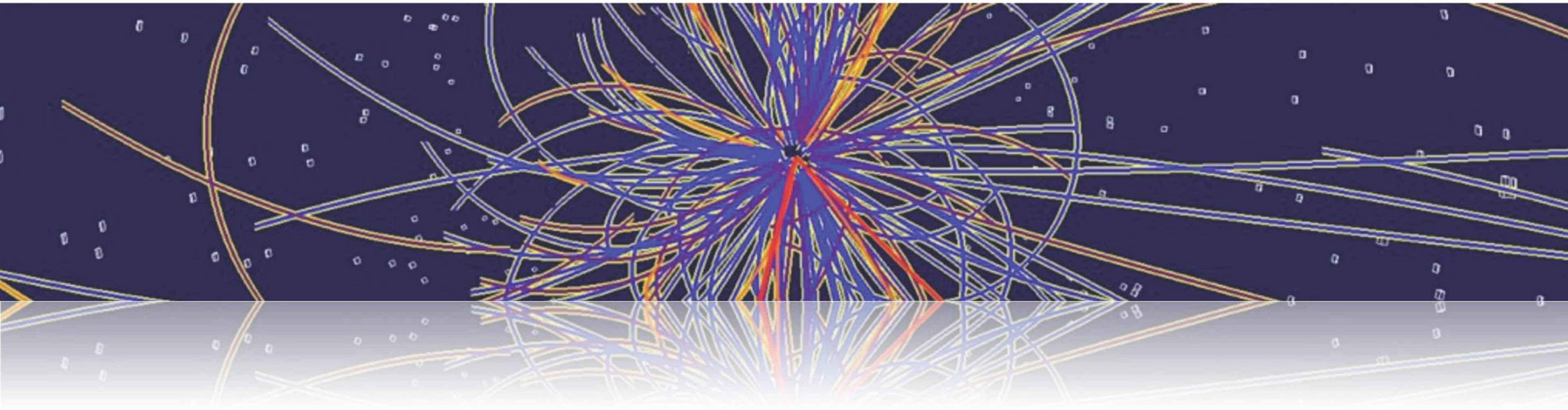


PDG ’08

[Summary of exp. results]



Monte Carlo Generators



Monte Carlo overview

Monte Carlo simulation ...

Numerical process generation based on random numbers

Method very powerful in particle physics

Event generation programs:

Pythia, Herwig, Isajet
Sherpa ...

Hard partonic subprocess +
fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response
of all produced particles ...

MC simulations in particle physics

Event Generator
simulate physics process
(quantum mechanics: probabilities!)

↓

Detector Simulation
simulate interaction with
detector material

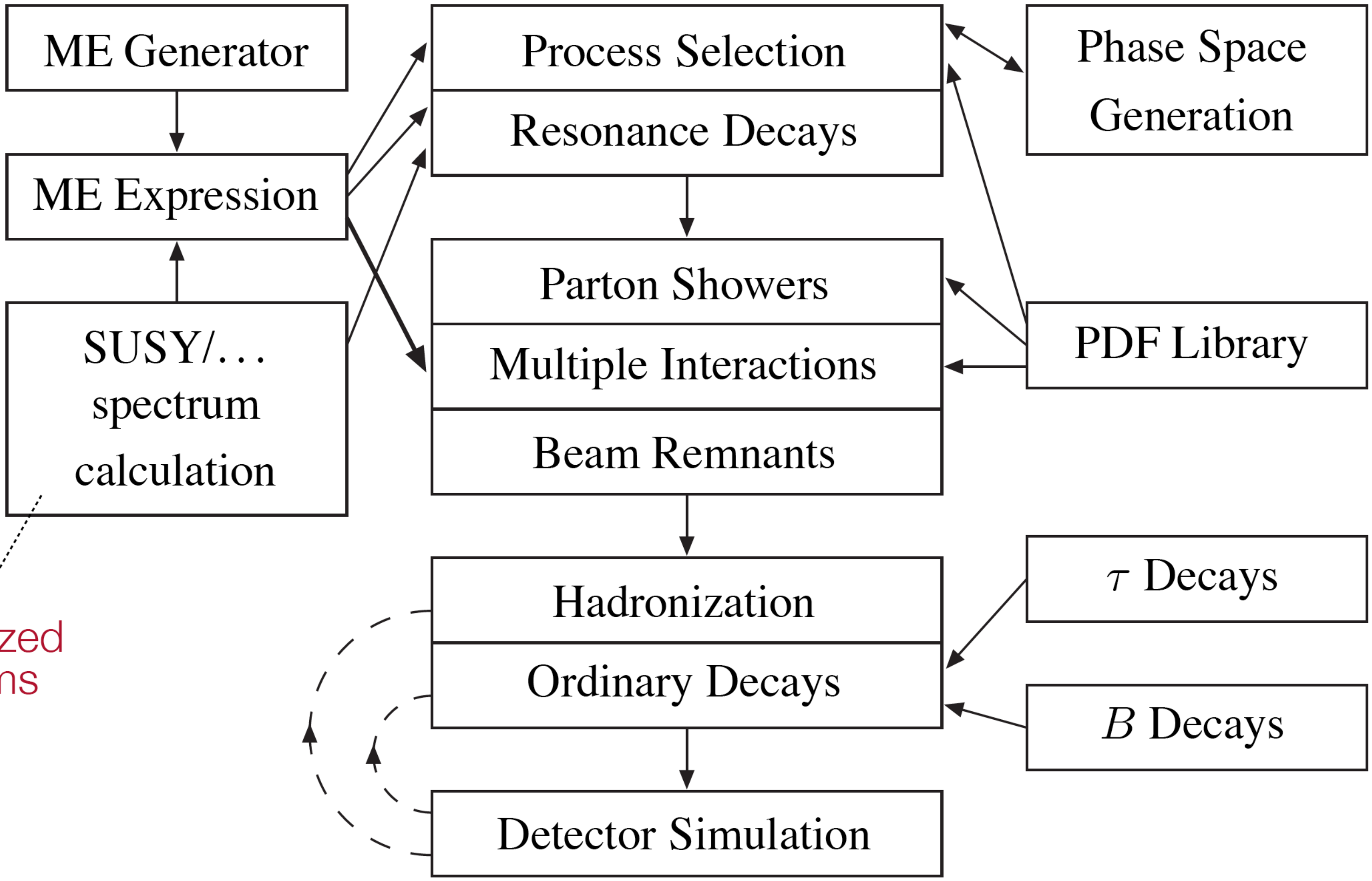
↓

Digitization
translate interactions with
detector into realistic signals

↓

Reconstruction/Analysis
as for real data

Monte Carlo overview



Use
specialized
programs

Pythia sub-processes

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g \gamma^*_T \to f_i \bar{f}_i$
136	$g \gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

Monte Carlo interfacing

Many specialized processes already available in Pythia ...

but, processes usually only implemented in lowest non-trivial order ...

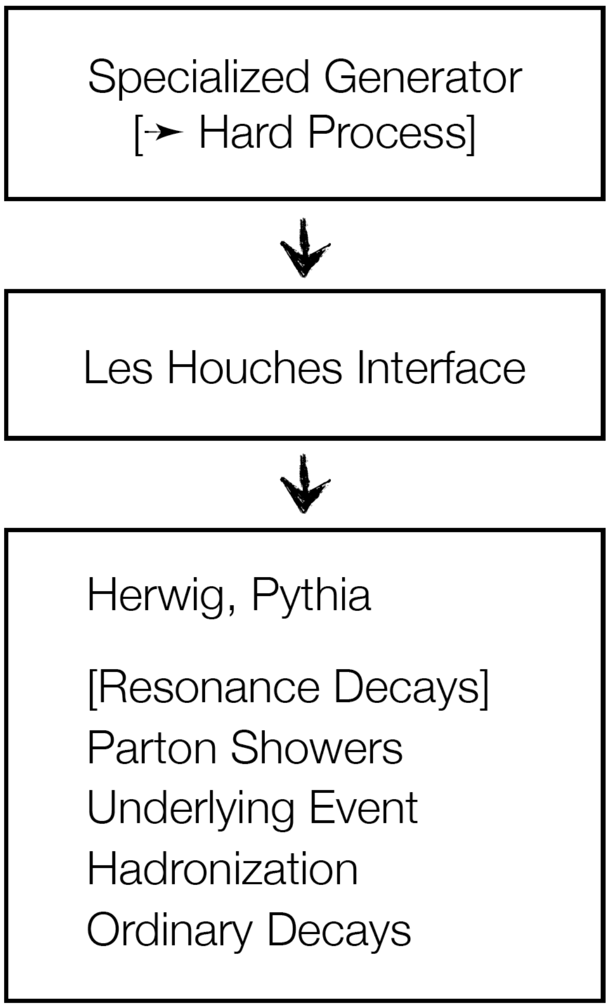
Need external programs that ...

- include higher order loop corrections or, alternatively, do kinematic dependent rescaling
- allow matching of higher order ME generators
  [otherwise need to trust parton shower description ...]
- provide correct spin correlations often absent in Pythia ...
  [e.g. top produced unpolarized, while $t \to bW \to bl\nu$ decay correct]
- simulate newly available physics scenarios ...
  [appear at rapid pace; need for many specialized generators]

Les Houches Accord ...

Specifies how parton-level information about the hard process and sequential decays can be encoded and passed on to a general-purpose generator.

Les Houches generator files



Specialized Generators:
[some examples]

AcerMC	:	ttbb, ...
ALPGEN	:	W/Z + ≤ 6j, nW + mZ + kH + ≤ 3j, ...
AMEGIC++	:	generic LO
CompHEP	:	generic LO
GRACE [+Bases/Spring]	:	generic LO [+ some NLO loops]
GR@PPA	:	bbbb
MadCUP	:	W/Z+ ≤ 3j, ttbb
HELAS & MadGraph	:	generic LO
MCFM	:	NLO W/Z+ ≤ 2j, WZ, WH, H+ ≤ 1j
O'Mega & WHIZARD	:	generic LO
VECBOS	:	W/Z+ ≤ 4j

Event Generator types

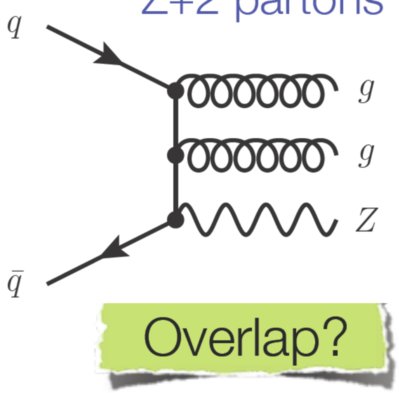
Type II : Leading order matrix element, parton shower & merging

i.e.: MEs for 2 ➛ n processes (e.g. W/Z + jets)
PS with LO generator [Pythia or Herwig]

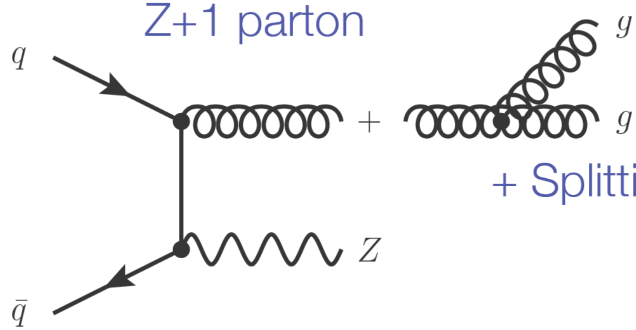
Examples: ALPGEN, MadGraph, Sherpa

Challenge: Remove overlap between jets from ME and jets from parton shower
[MLM matching, CKKW]

Z+2 partons



Z+1 parton



+ Splitting

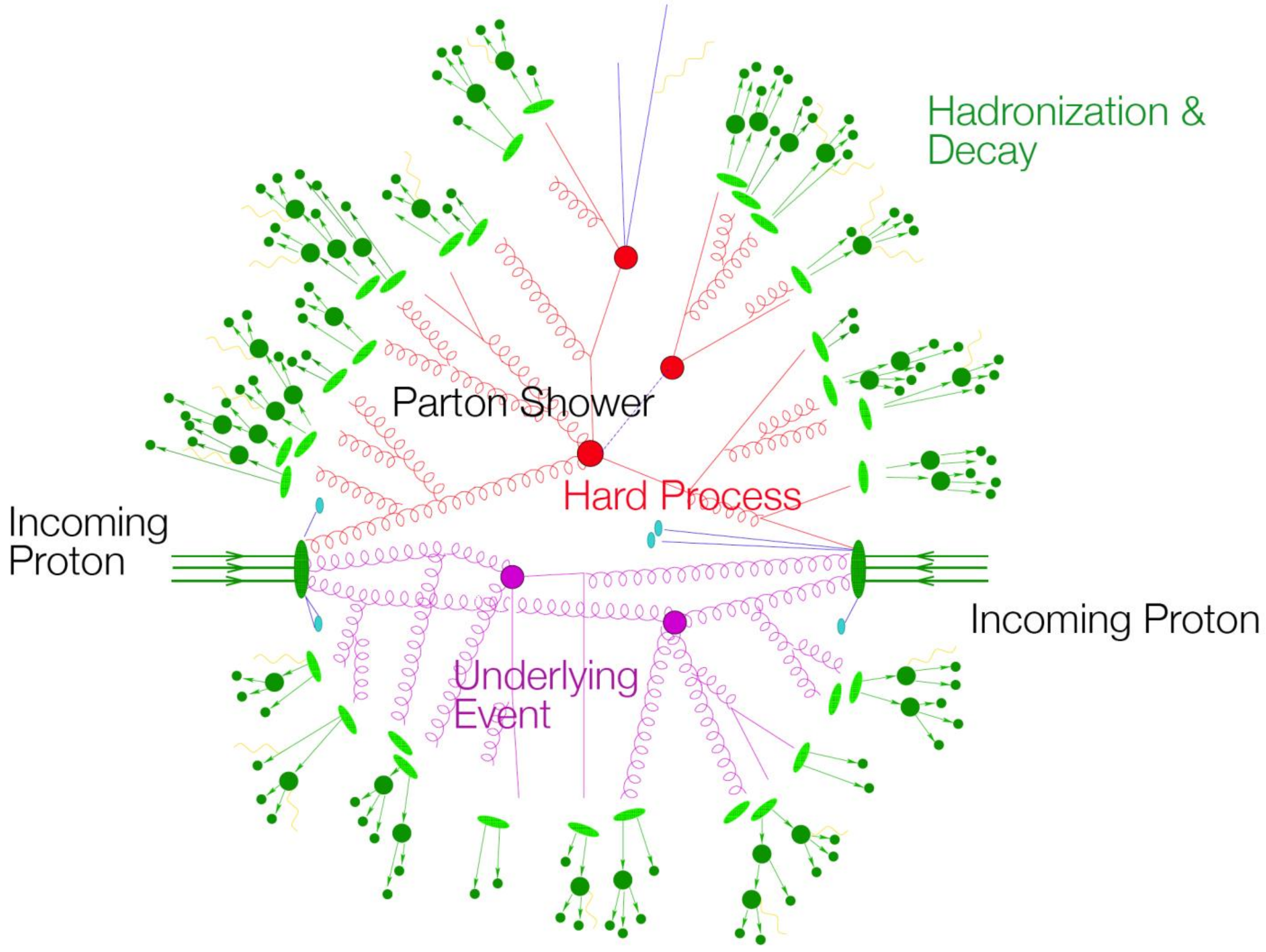
ME+PS
- Herwig
- Pythia
- SingleTop, TopRex
- Phantom
- AcerMC
- GRAPPA
- CompHEP

ME+PS+merging
- Alpgen
- MadGraph
- Sherpa

NLO+PS
- MC@NLO
- POWHEG

[F. Maltoni]

From Partons to Jets



[T. Gleisberg et al., JHEP02 (2004) 056]

From Partons to Jets

From partons to
color neutral hadrons:

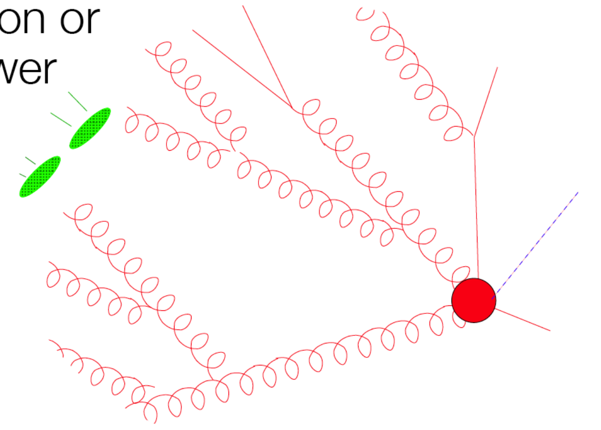
Fragmentation:

Parton splitting into other partons
[QCD: re-summation of leading-logs]
[“Parton shower”]

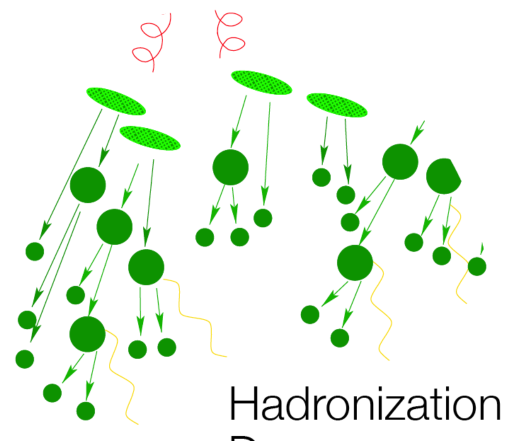
Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]



Fragmentation or
Parton Shower



Hadronization &
Decays

Parton splitting

$$d\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)dz$$

Splitting probability
determined by splitting functions $P_{q\to qg}$

$$P_{\mathrm{q}\to\mathrm{qg}} = \frac{4}{3}\frac{1+z^2}{1-z}$$

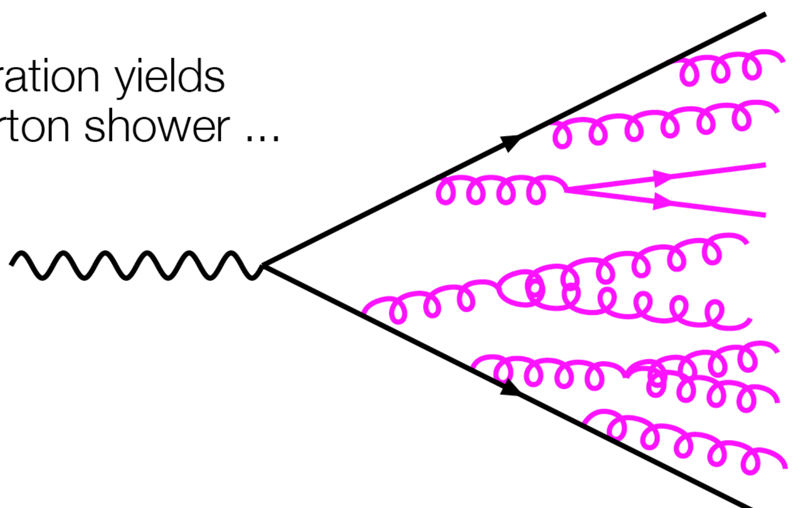
$$P_{\mathrm{g}\to\mathrm{gg}} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$

$$P_{\mathrm{g}\to\mathrm{q\bar{q}}} = \frac{n_f}{2}(z^2+(1-z)^2)$$

Same splitting functions
as used for PDF evolution

z : fractional momentum of radiated parton
n_f : number of quark flavours

Iteration yields
parton shower ...



Need soft/collinear cut-offs to
avoid non-perturbative regions ...
[divergencies!]

Details model-dependent

e.g. $Q > m_0 = \min(m_{ij}) \approx 1$ GeV,
$z_{min}(E,Q) < z < z_{max}(E,Q)$ or
$p_\perp > p_{\perp min} \approx 0.5$ GeV

Hadronization models

Non-perturbative transition from partons to hadrons ...
[Modeling relies on phenomenological models available]

Models based on MC simulations
very successful:

Generation of complete final states ...
[Needed by experimentalists in detector simulation]

Caveat: tunable ad-hoc parameters

Most popular MC models:

Pythia	:	Lund string model
Herwig	:	Cluster model

Lund String Model

Lund String Model

[Andersson et al., Phys. Rep. 97 (1983) 31]

QCD potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(1/r^2)}{r} + kr$$

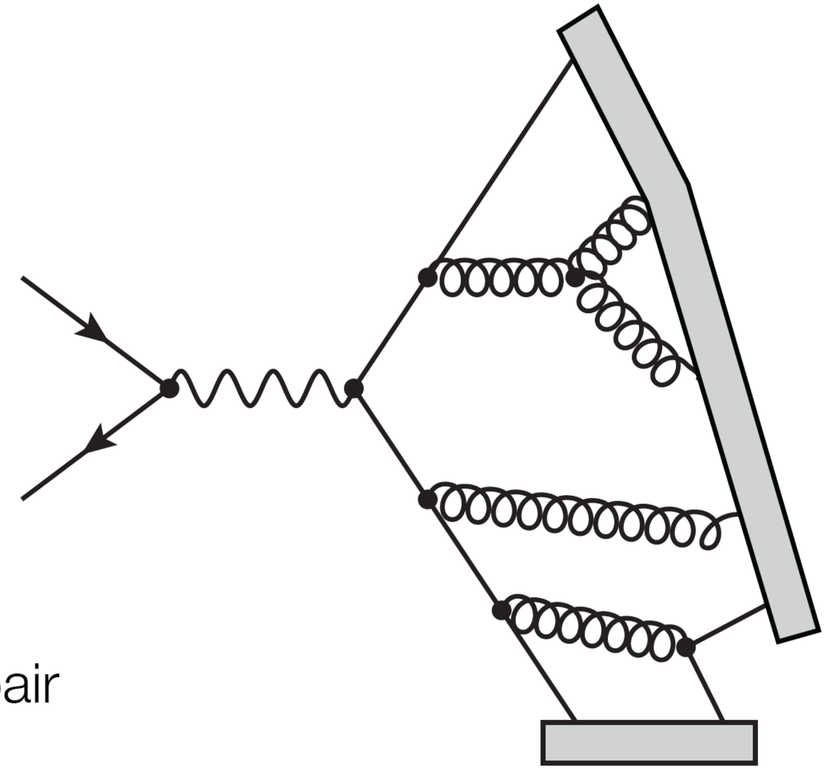
String formation between initial quark-antiquark pair

String breaks up if potential energy large enough new quark-antiquark pair

Gluons = 'kinks' in string

At low energy: hadron formation

Very widely used ...
[default in Pythia]



After: Ellis et al.,
QCD and Collider Physics

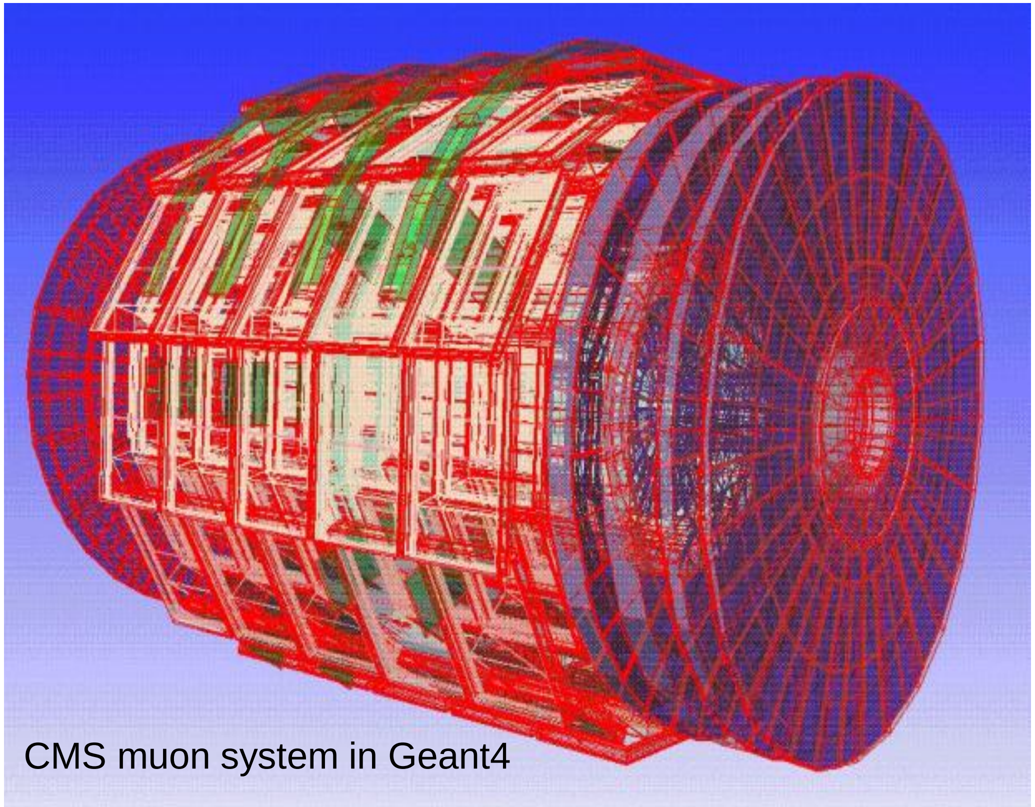
Detector simulation

GEANT
Geometry And Tracking

Detailed description of detector geometry
[sensitive & insensitive volumes]

Tracking of all particles through detector material ...

➛ Detector response



Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C^{++}]

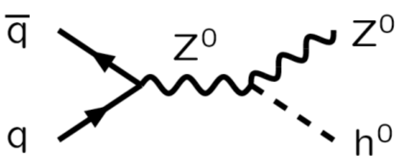
Overview of MC generators

Structure of basic generator process [by order of consideration]

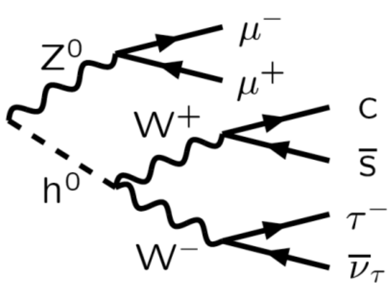
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled; at small

Matrix elements (ME)

1. Hard subprocess:
   $|M|^2$, Breit Wigners, PDFs

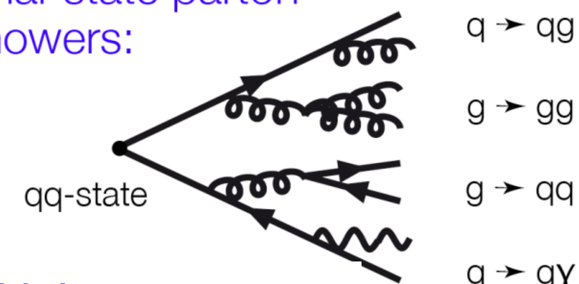


2. Resonance decays:
   Includes particle correlations

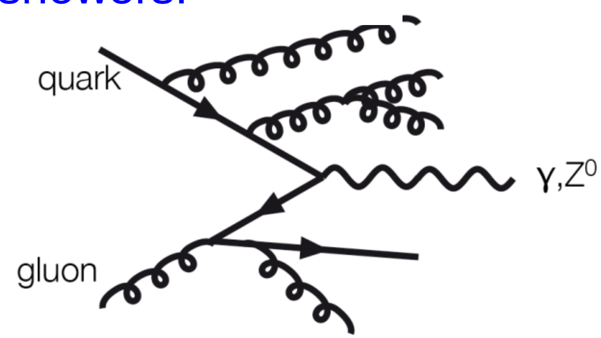


Parton Shower (PS)

3. Final-state parton
   showers:



4. **Initial-state parton showers:**



[from G.Herten]

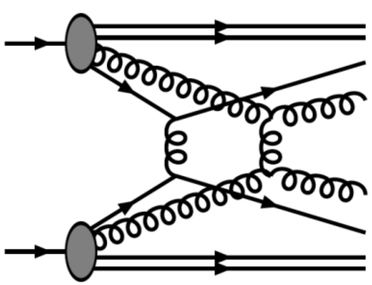
Overview of MC generators

Structure of basic generator process [by order of consideration]

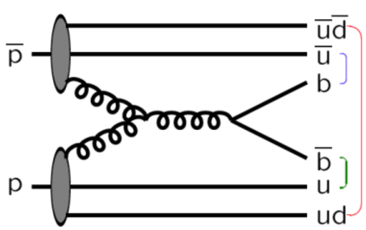
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled; at small

Underlying Event (UE)

5. Multi-parton interaction:

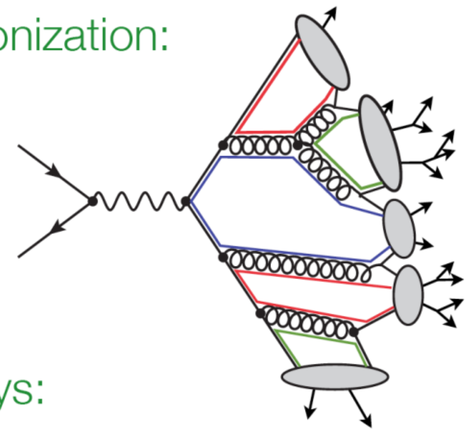


6. Beam remnants:

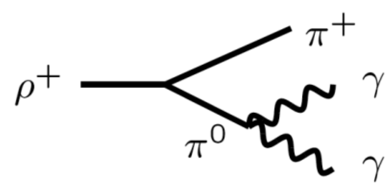


Stable Particle State

7. Hadronization:

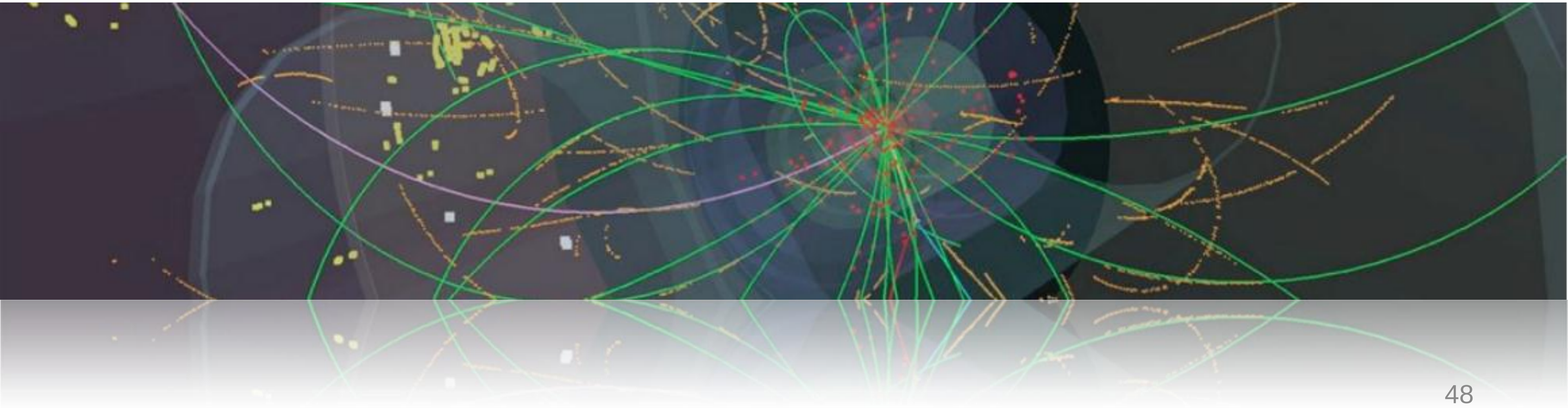


8. Decays:



[from G.Herten]

Luminosity
and cross-section measurements



Cross section & Luminosity

Luminosity
[Machine parameter]

$$\dot{N} = L \cdot \sigma$$

Event Rate
[Measured]

Cross Section

Cross section & Luminosity

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

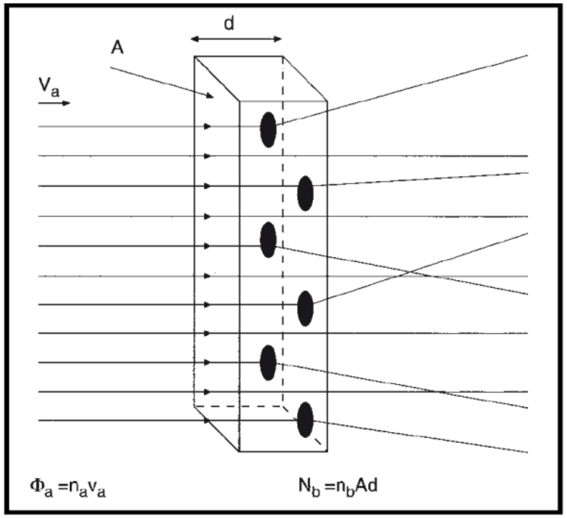
Luminosity

determined by accelerator, triggers, …

Efficiency

many factors, optimized by experimentalist

Cross section & Luminosity



$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

Φ_a : flux
n_a : density of particle beam
v_a : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

$\dot{N}$: reaction rate
N_b : target particles within beam area
σ_a : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

$$\dot{N} \equiv L \cdot \sigma$$

$$N = \sigma \cdot \underbrace{\int L\, dt}_{\text{integrated luminosity}} \qquad \sigma = N/L$$

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

$$L = f \frac{n N_a N_b}{A} = f \frac{n N_a N_b}{4\pi \sigma_x \sigma_y}$$

LHC:

N_x	~	10^{11}
A	~	.0005 mm^2
n	~	2800
f	~	11 kHz
L	~	10^{34} cm^{-2} s^{-1}

N_a : number of particles per bunch (beam A)
N_b : number of particles per bunch (beam B)
U : circumference of ring
n : number of bunches per beam
v : velocity of beam particles
f : revolution frequency
A : beam cross-section
σ_x : standard deviation of beam profile in x
σ_y : standard deviation of beam profile in y

Luminosity determination @ LHC

Absolute Methods:

Accuracy: 10%

Determination from LHC parameters; van-der-Meer separation scans ...
Rate measurement for standard candle processes ...

LHC Examples:

Rate of pp ➛ Z/W ➛ $\ell\ell/\ell\nu$ [needs: electroweak cross sections]

Accuracy: 5-10%
[PDF knowledge, ...]

Rate of pp ➛ $\gamma\gamma$ ➛ $\mu\mu$, ee [needs: QED & photon flux]

Accuracy: 1% ?
[TDR; needs forw. tagging]

Optical theorem: $\sigma_{tot} \sim \text{Im}\, f(0)$ [needs: forward elastic and total inel. x-sec]

Elastic scattering in Coulomb region ...

Accuracy: 5-10%
[needs σ_{tot}; needs forw. instrumentation]
TOTEM

Combination of the above ...

Accuracy: 2-3%

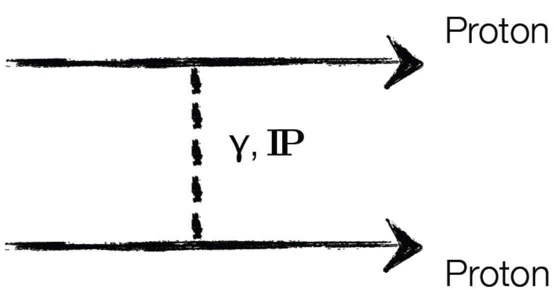
Relative Methods:

Particle counting; **LUCID @ ATLAS; HF, Pixels @ CMS**
[needs to be calibrated for absolute luminosity]

Aim: Luminosity accuracy of 2-3% ...

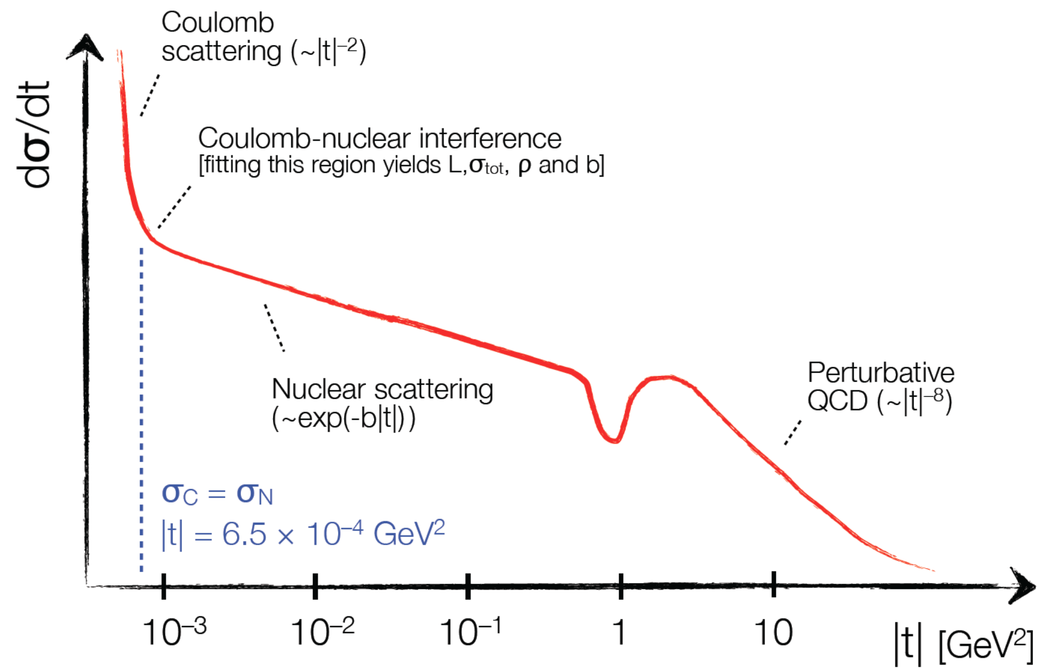
Luminosity and elastic scattering

Elastic Scattering:



$$t = (p_i - p_i') \sim p^2\theta^2$$

Elastic Scattering at low t is sensitive to exactly known Coulomb amplitude ...



Shape of elastic scattering distribution can also be used to determine total cross section, σ_{tot}, and the parameters ρ and b ...

Perform fit to:

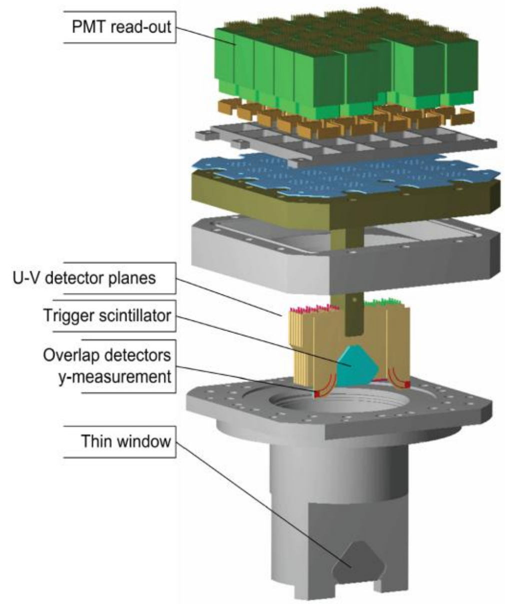
$$\frac{dN}{dt} = L\left(\underbrace{\frac{4\pi\alpha^2}{|t|^2}}_{\text{Coulomb Scattering}} - \underbrace{\frac{\alpha\rho\sigma_{\mathrm{tot}}e^{\frac{-b|t|}{2}}}{|t|}}_{\text{Coulomb/nuclear Interference}} + \underbrace{\frac{\sigma_{\mathrm{tot}}^2(1+\rho^2)e^{-b|t|}}{16\pi}}_{\text{Nuclear Scattering}}\right)$$

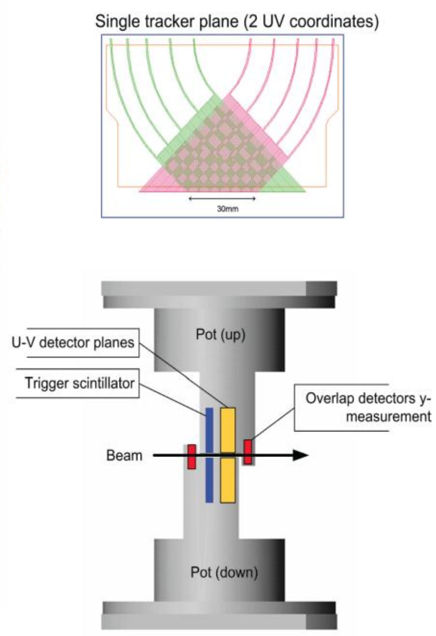
with:

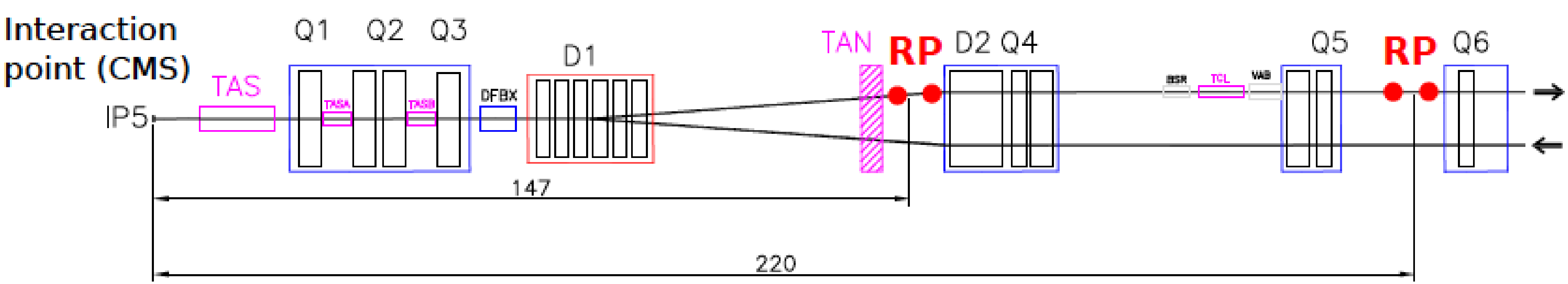
- ρ : ratio of the real to imaginary part of the elastic forward amplitude
- b : nuclear slope
- σ_{tot} : total pp ➝X cross section

Roman Pots (Totem and Alfa)

- Measurement of p-p elastic scattering
- Roman Pots used to move detectors near to stable beam.



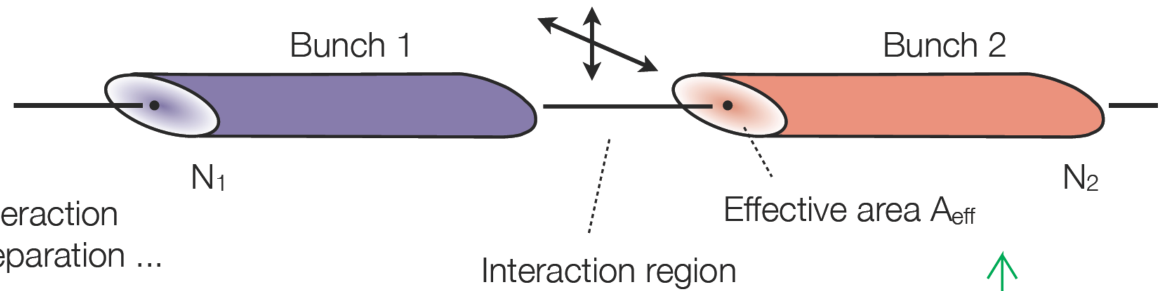


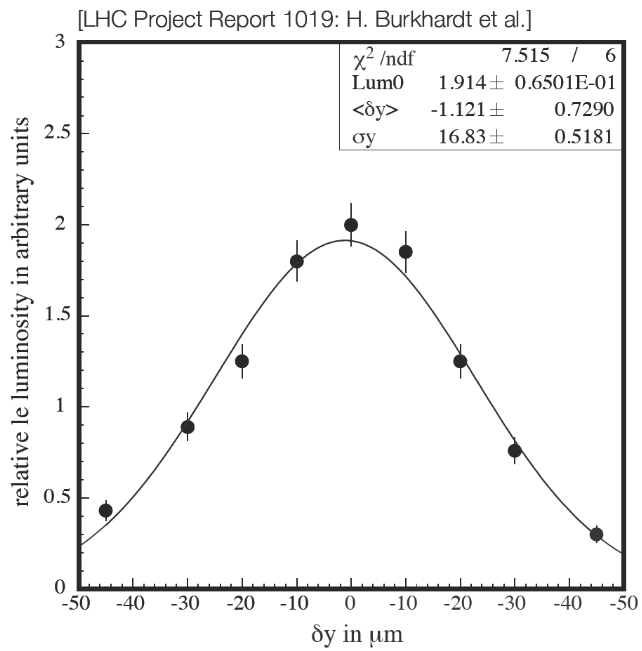


Van-der-Meer separation scan

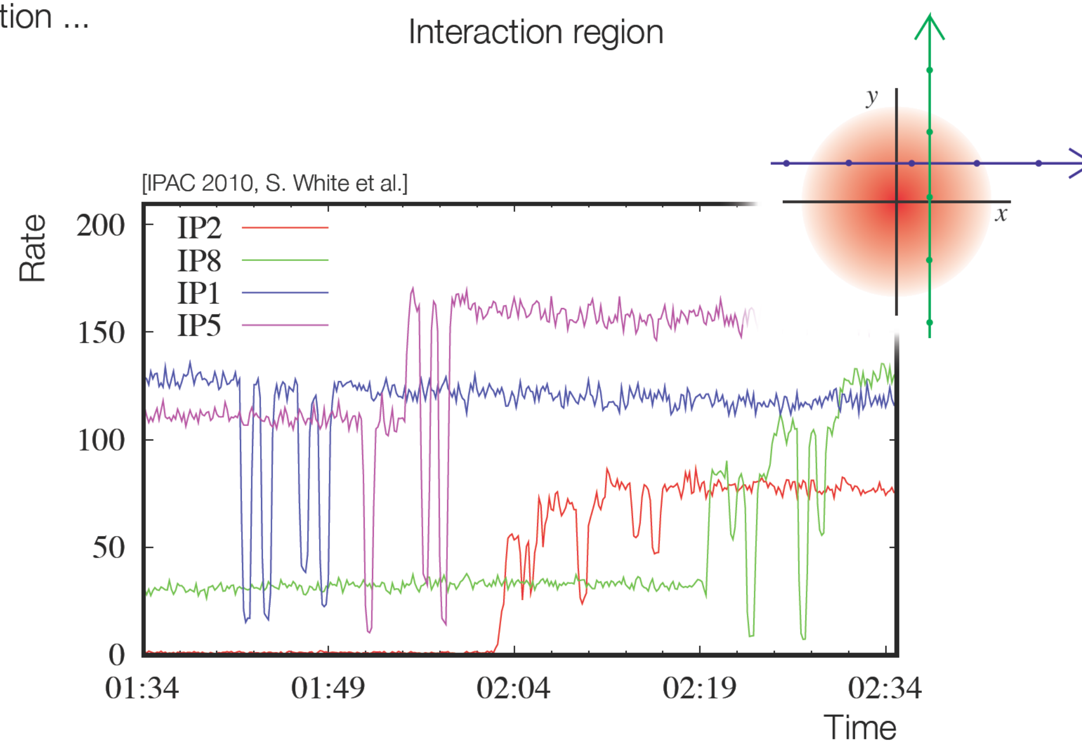
Determine beam size ...

measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...



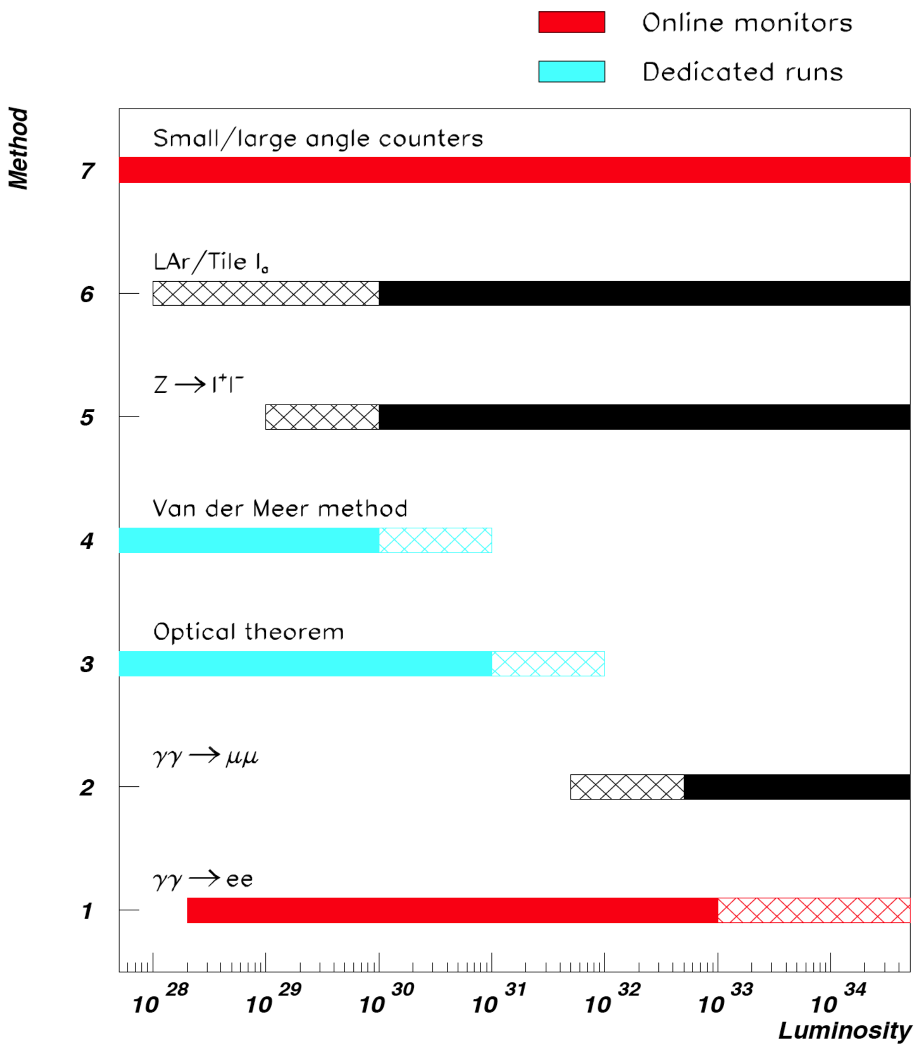


$$\frac{L}{L_0} = \exp\left[-\left(\frac{\delta_x}{2\sigma_x}\right)^2 - \left(\frac{\delta_y}{2\sigma_y}\right)^2\right]$$



First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].

Luminosity determination @ LHC

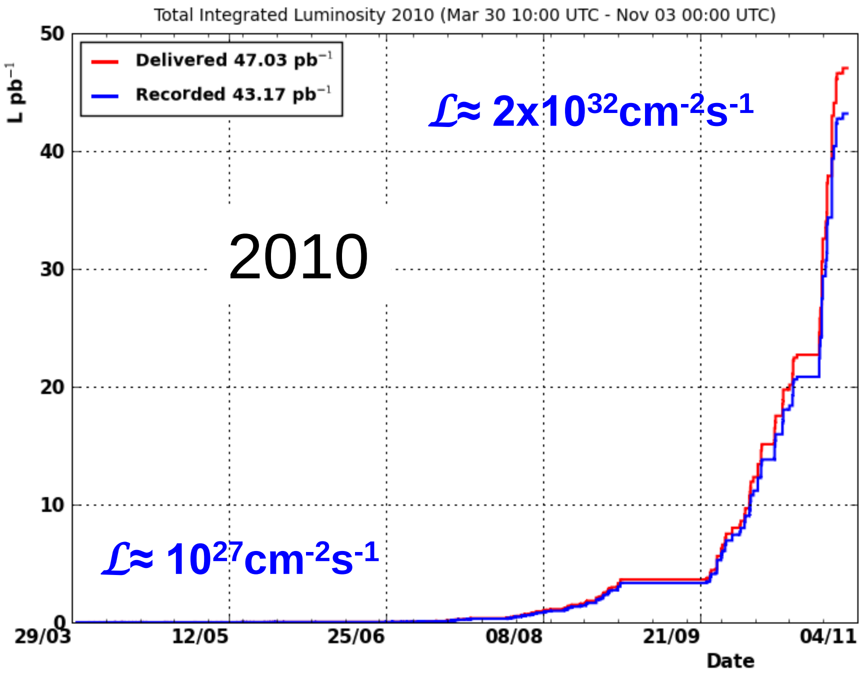


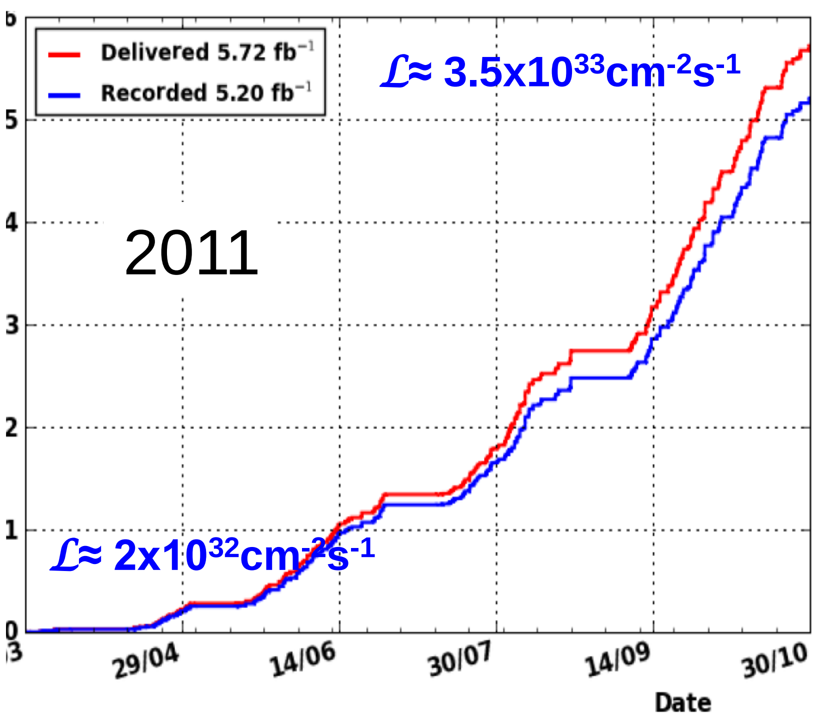
Methods as
summarized in ATLAS TDR

[ATLAS Technical Design Report, Vol. I]

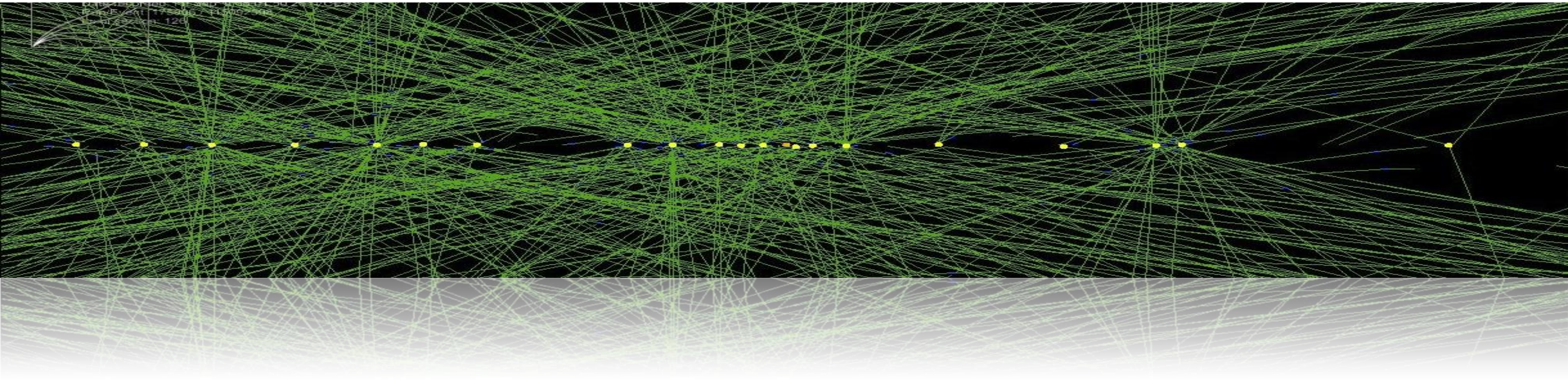
Instantaneous and integrated Luminosity

	Instantaneous (max)	Integrated
2010:	$2.x10^{32}$ $cm^{-2}s^{-1}$	47 pb^{-1}
2011:	$3.5x10^{33}$ $cm^{-2}s^{-1}$	5.7 fb-1





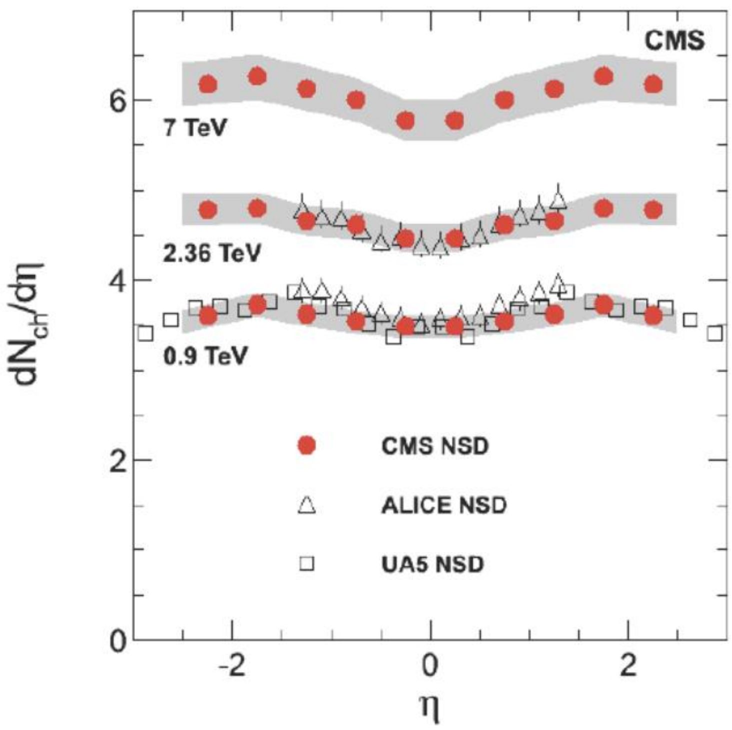
Minimum bias events

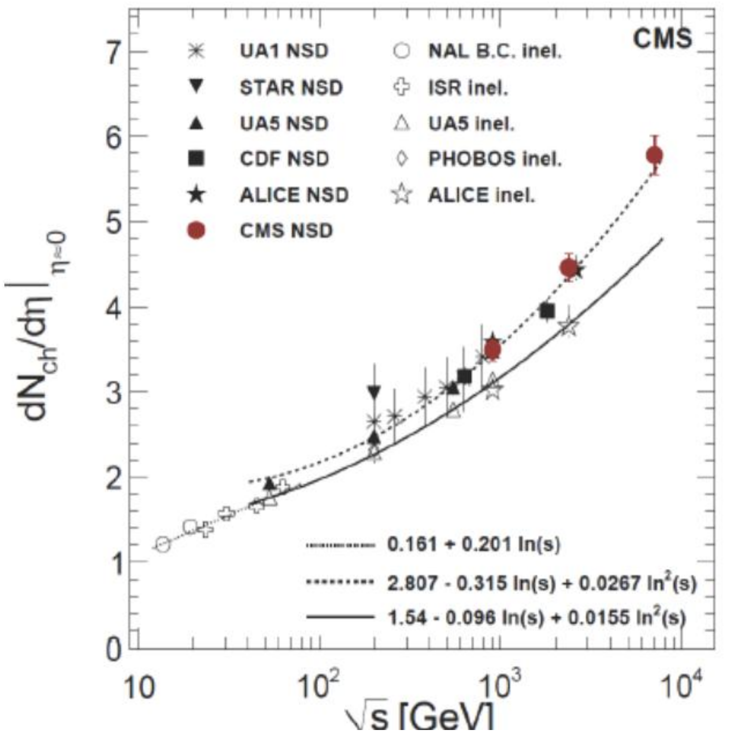


Characteristics of inelastic p-p collisions

Particle density in minimum bias events

Soft QCD (PT threshold on tracks: 50 MeV)

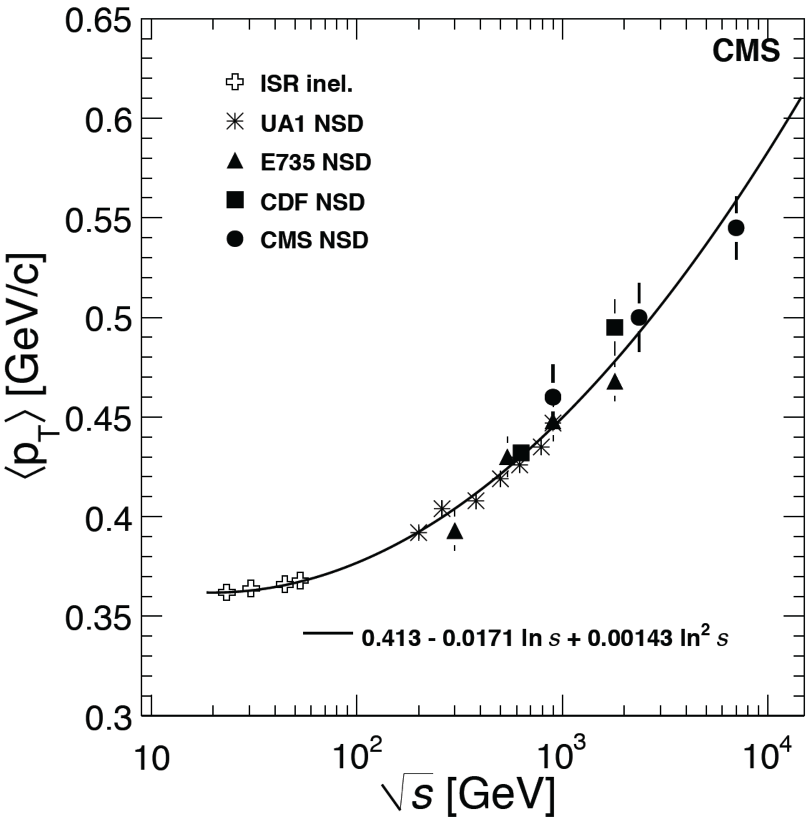




Particle density in data rises faster than in model predictions.
Tuning of MC generators was needed.

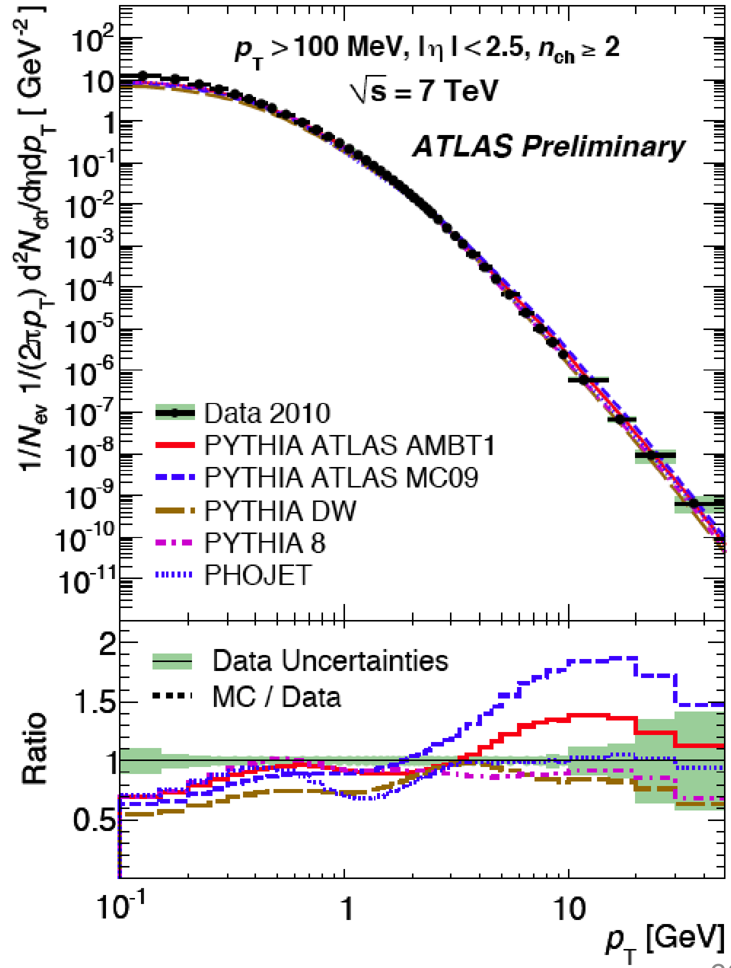
Charged particle p_T spectrum

$<p_T> = 0.545$
$\pm$ 0.005 (stat.)
$\pm$ 0.015 (syst.) GeV/c



dN_{ch}/dp_T

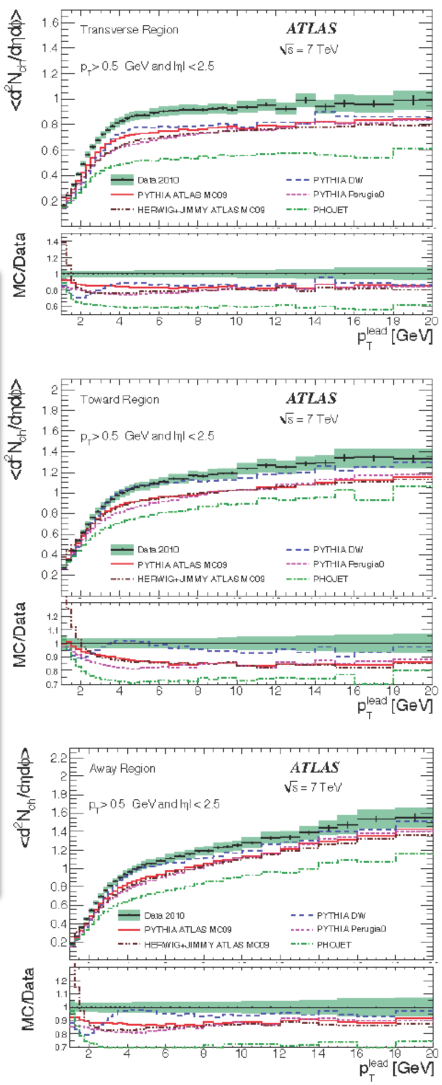
p_T > 100 MeV
$|\eta|$ < 2.5
$N_{ch} \geq 2$

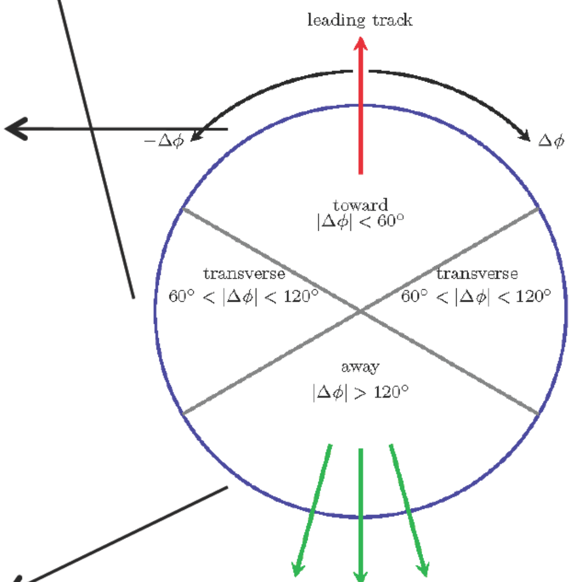


Underlying event

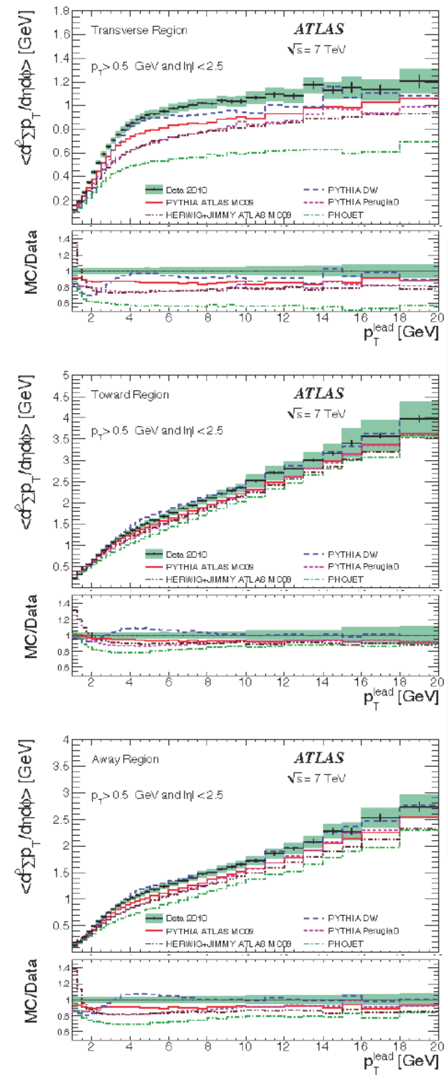
Particle momentum flow in regions defined wrt leading track

Multiplicity vs P_T





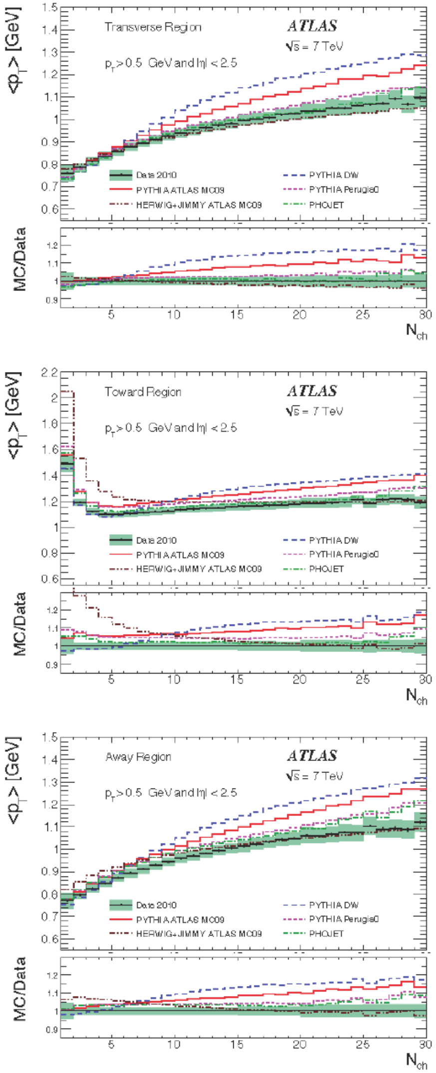
Sum P_T vs P_T



arXiv:1012.0791

Underlying event

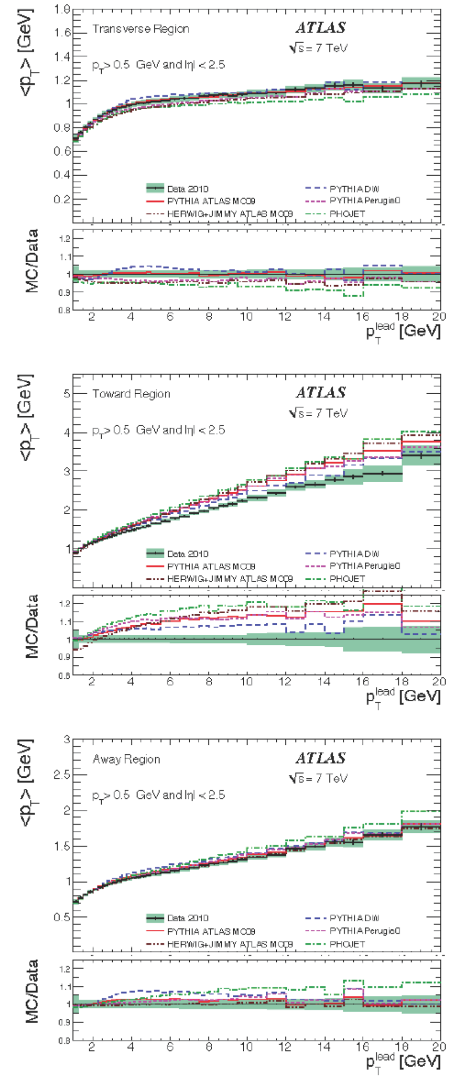
Mean P_T vs Multiplicity



From these comparisons: determine best "tunes" for underlying event.

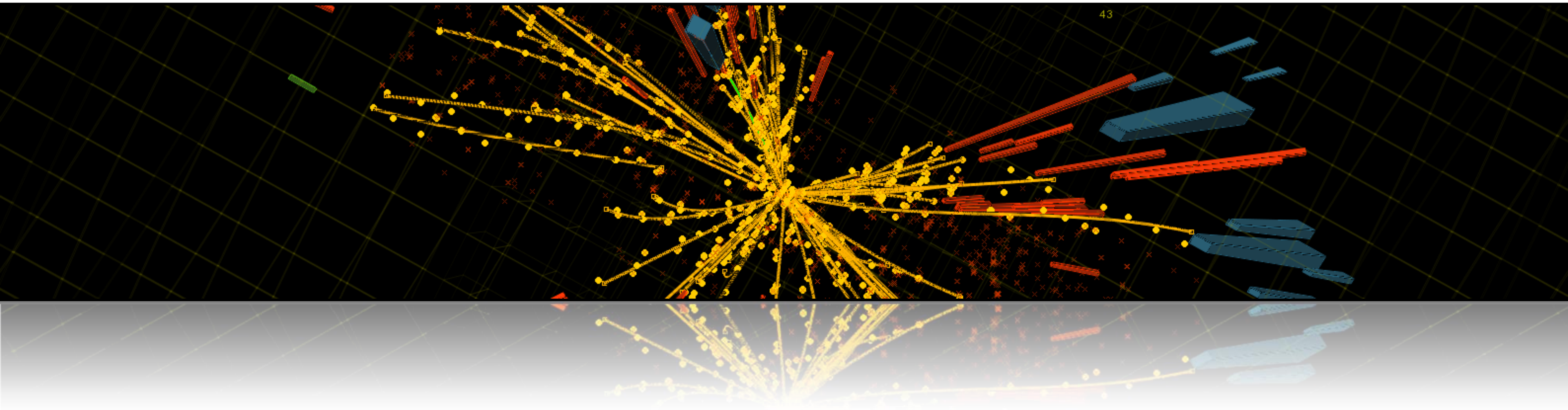
In practice: tuning of soft QCD model in PYTHIA

Tuning is important for data-MC agreement further down; particle isolation (e.g. in lepton identification) and missing energy (ME_T)



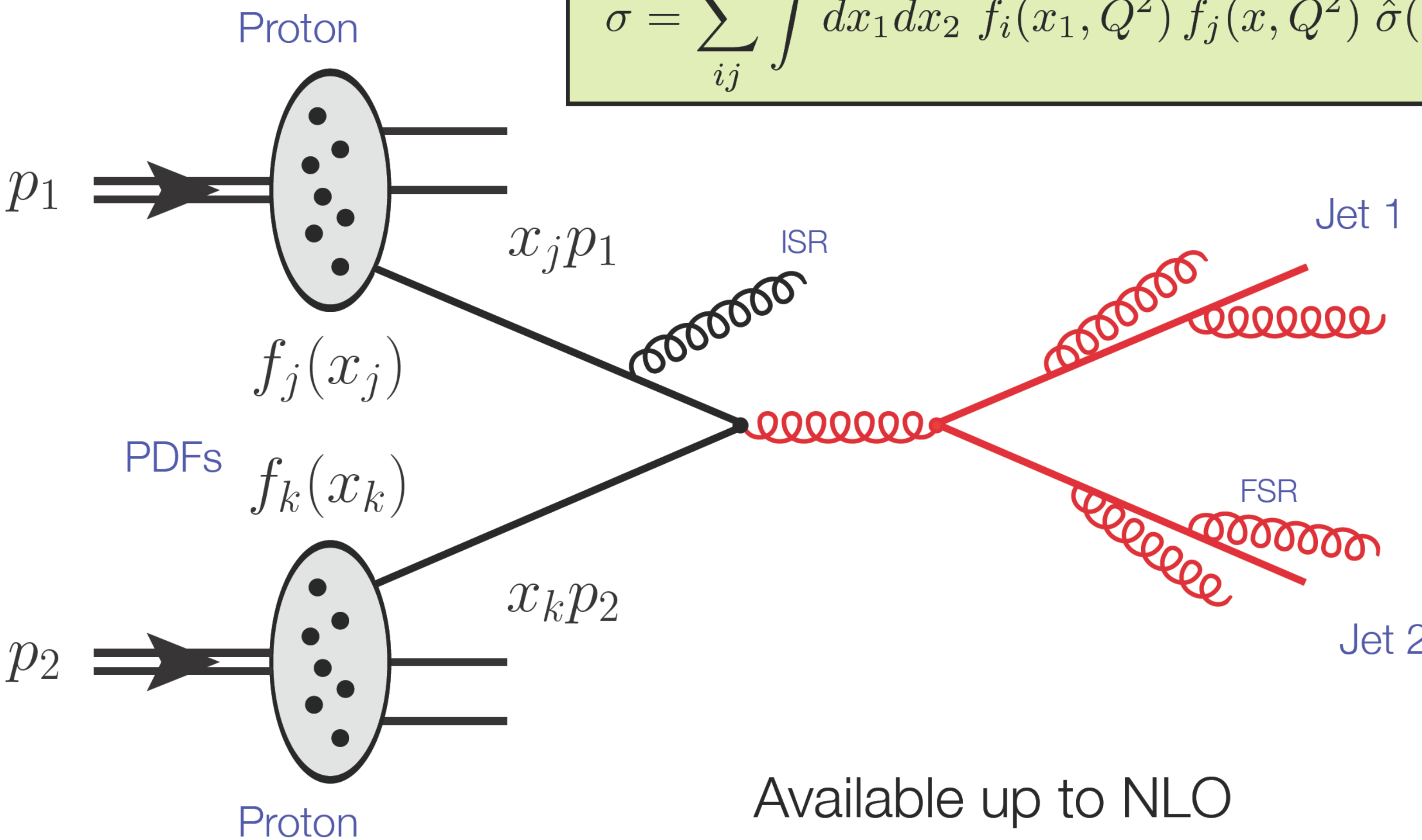
Mean P_T vs P_T

Jet physics



Jet production @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\, f_j(x, Q^2)\; \hat{\sigma}(Q^2)$$



Available up to NLO

First NNLO calculations becoming available ...

Higher orders

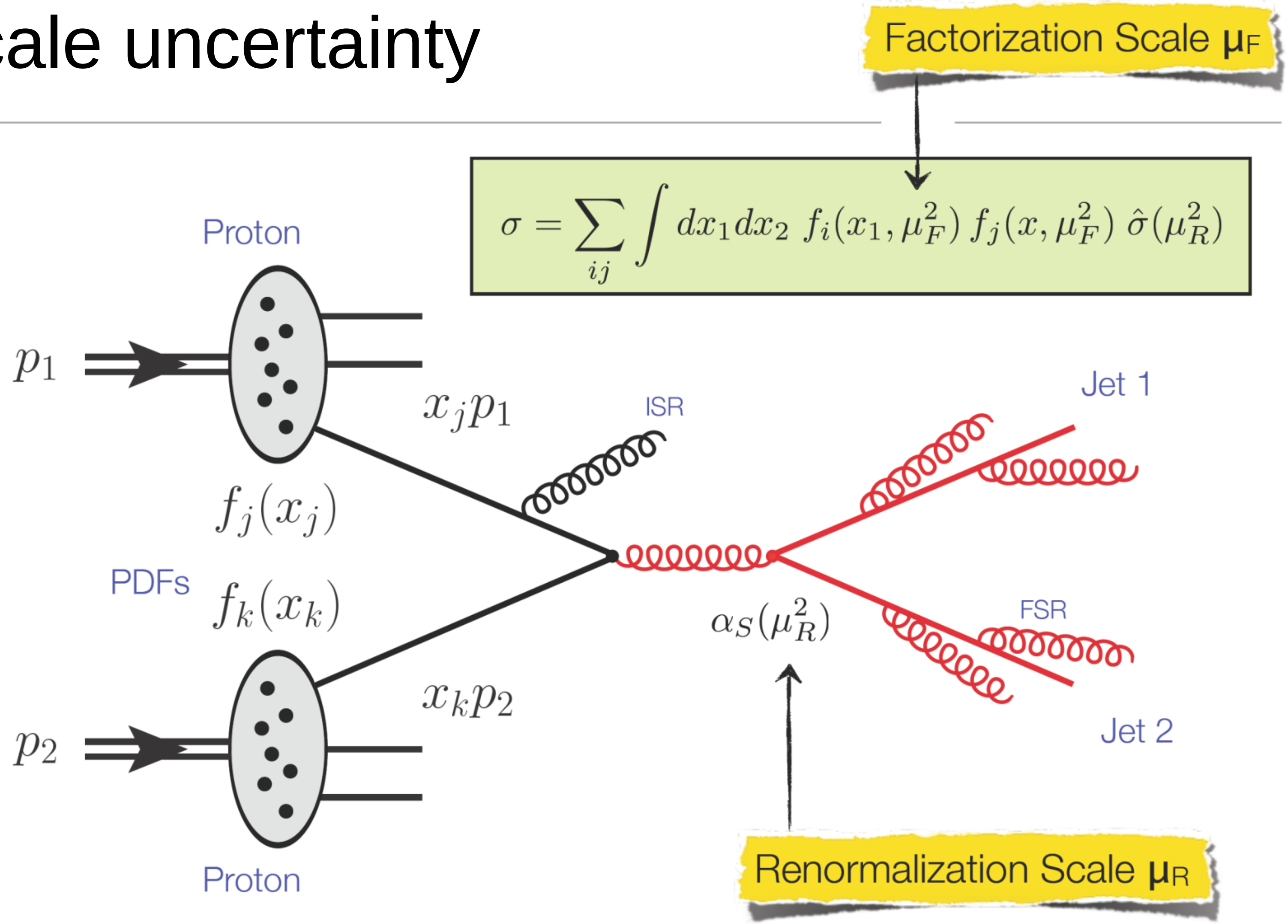
At least next-to-leading order (NLO) required
to compare to precision measurements
[First NNLO calculations becoming available ...]

Various divergencies; artifacts of perturbation theory;
the full theory gives finite results ...
[But we don't know how to solve it]

Ultraviolet (UV) divergences, i.e. at very large momenta
Solution: renormalization; choice of correct scale ...
["Status of peaceful coexistence with divergences", S.D. Drell]

Infrared (IR) divergences, i.e. at very small momenta
Solution: cancellations, factorization, IR-safe observables

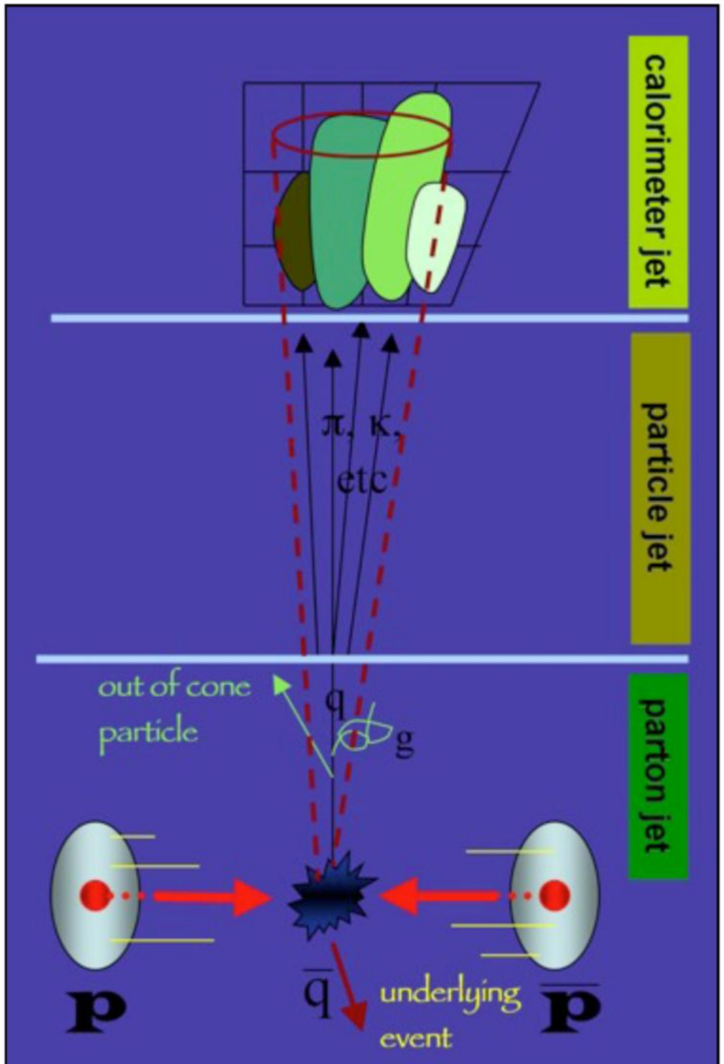
Scale uncertainty

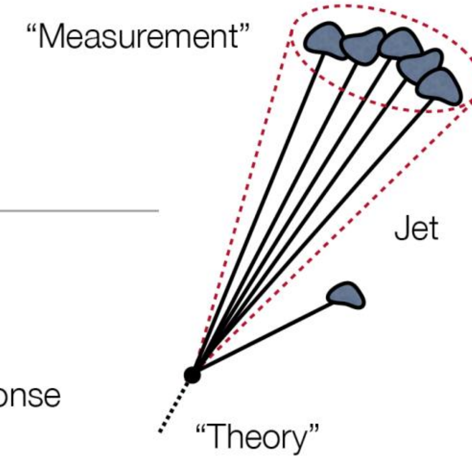


The default renormalization and factorization scales (μ_R and μ_F respectively) are defined to be equal to the p_T of the leading jet in the event

Scale uncertainty estimation: vary μ_R, μ_F within $[\mu_R/2, 2\mu_R]$ and $[\mu_F/2, 2\mu_F]$

Jet properties measurement





Calorimeter Jet
[extracted from calorimeter clusters]

Understanding of detector response
Knowledge about dead material
Correct signal calibration
Potentially include tracks

From measured energy to particle energy

Compensate energy loss due to neutrinos, nuclear excitation ...

Hadron Jet
[might include electrons, muons ...]

Hadronization
Fragmentation
Parton shower
Particle decays

From particle energy to original parton energy

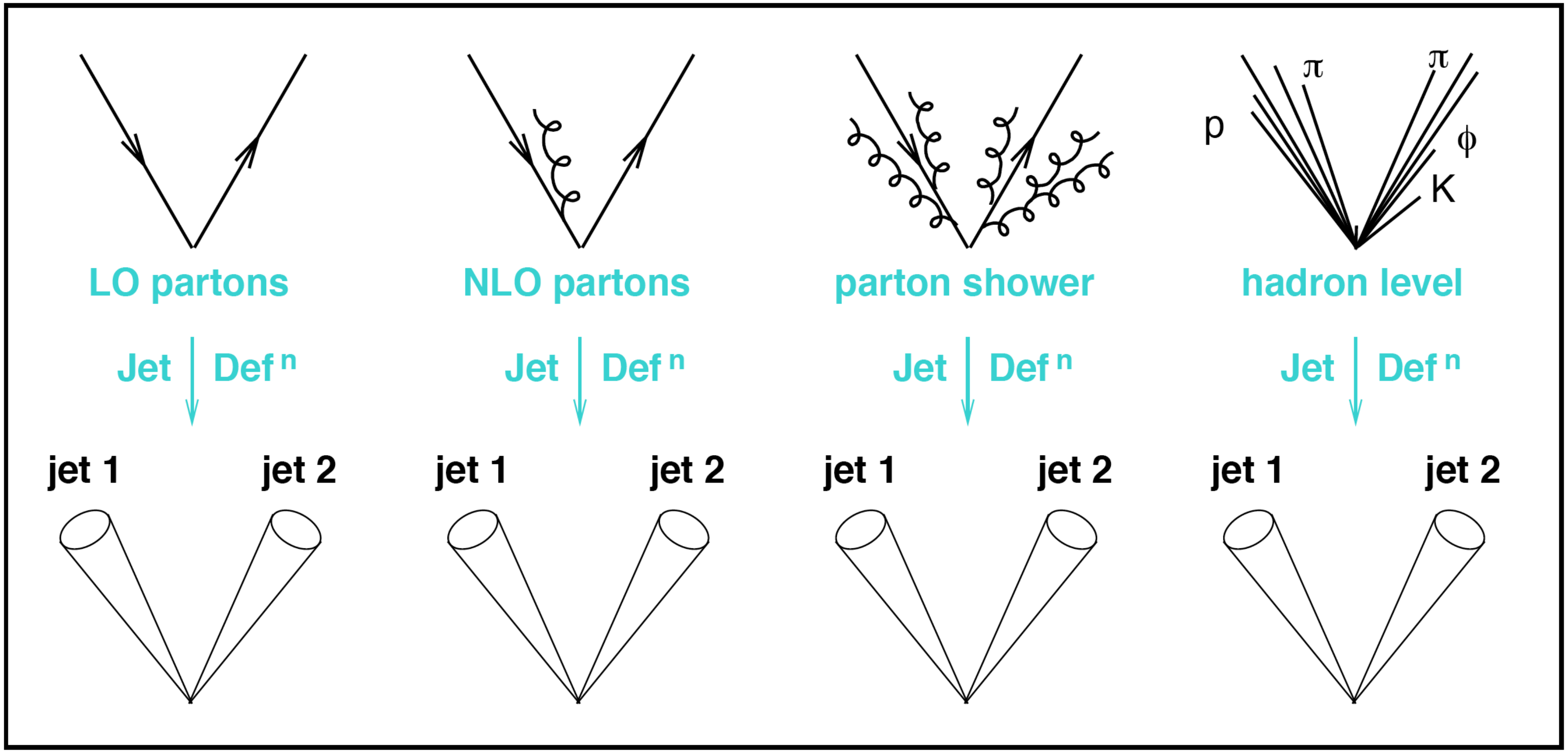
Compensate hadronization; energy in/outside jet cone
...

Parton Jet
[quarks and gluons]

Proton-proton interactions
Initial and final state radiation
Underlying event

Needs Calibration

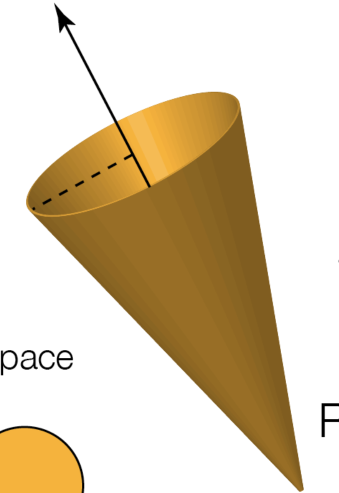
Jet properties measurement



Jets may look different at different levels

Robust jet definition ➛ stable on all jet levels

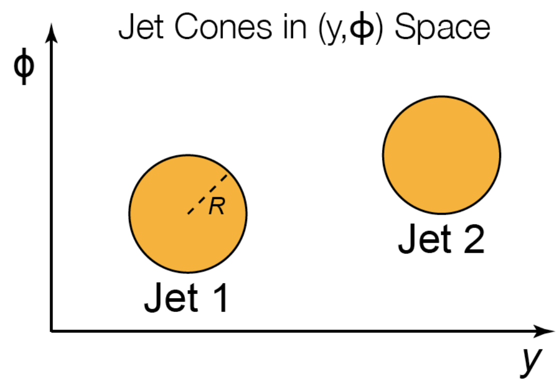
Jet reconstruction



Iterative cone algorithms:

Jet defined as energy flow within a cone of radius R in (y,ϕ) or (η,ϕ) space:

$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$



Sequential recombination algorithms:

Define distance measure d_{ij} ...

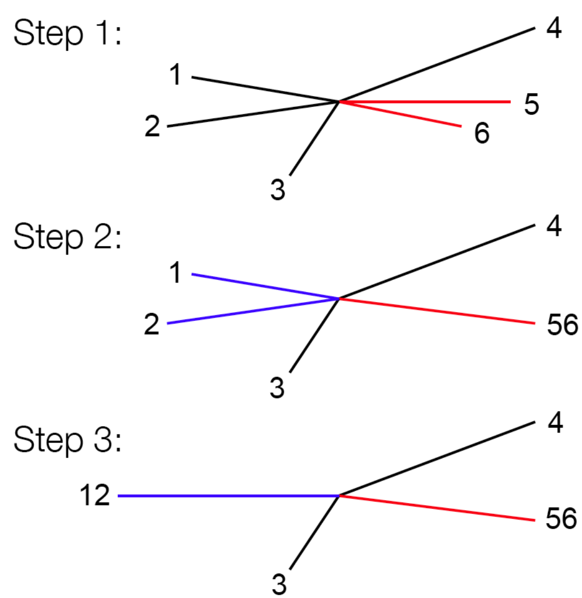
Calculate d_{ij} for all pairs of objects ...

Combine particles with minimum d_{ij} below cut ...

Stop if minimum d_{ij} above cut ...

e.g. k_T-algorithm:
[see later]

$$d_{ij} = \min\left(k_{T,i}^2, k_{T,j}^2\right) \frac{\Delta Rij}{R}$$



Sequential recombination

Jet algorithms performance

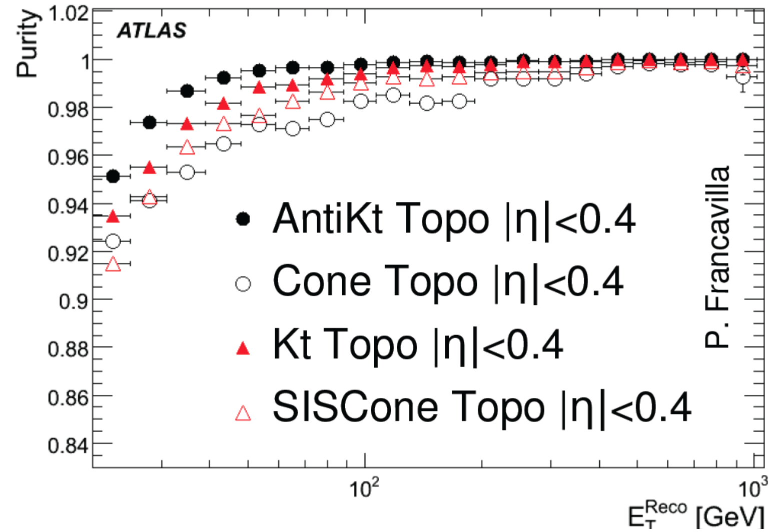
Anti-kt clustering algorithm:

in distance formula
replace P_T^2 by P_T^{2p}

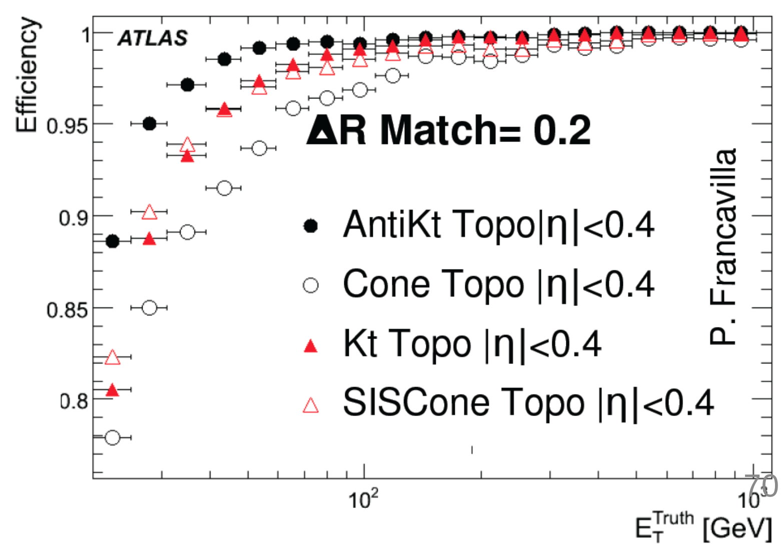
p=1 : standard Kt
p=-1 : anti-Kt

$$D_{ij} = \min(P_{Ti}^2, P_{Tj}^2)\frac{\Delta R_{ij}^2}{R^2}$$

Purity = $N^{Reco}_{Matched}$ / N^{Reco}

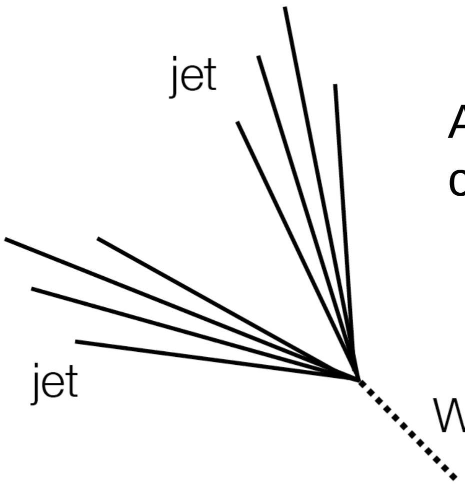


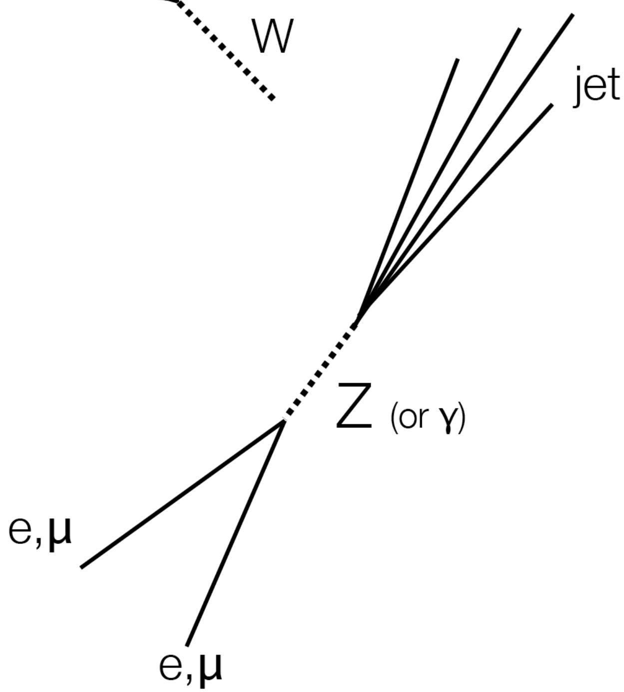
Efficiency = $N^{Truth}_{Matched}$/ N^{Truth}



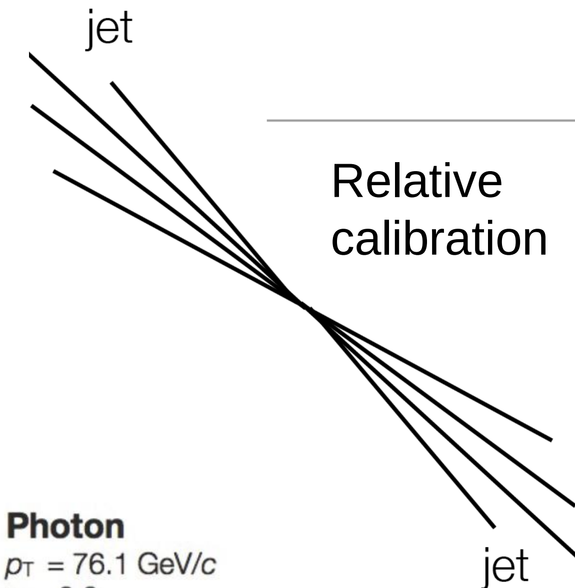
Jet energy calibration

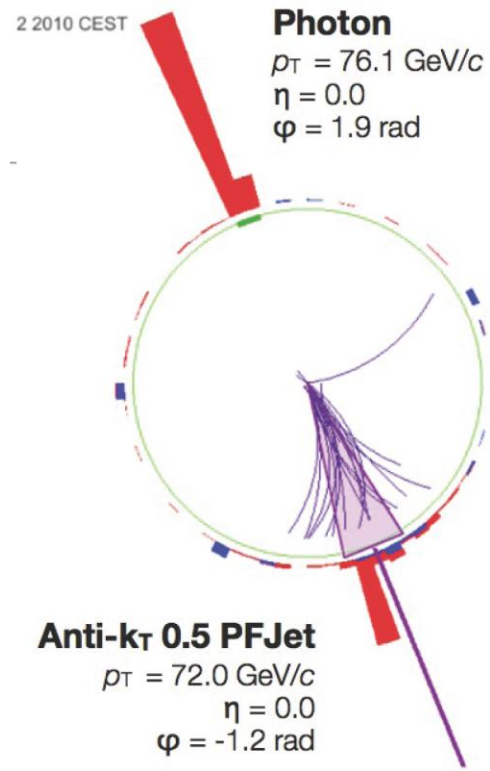
Absolute calibration





Relative calibration

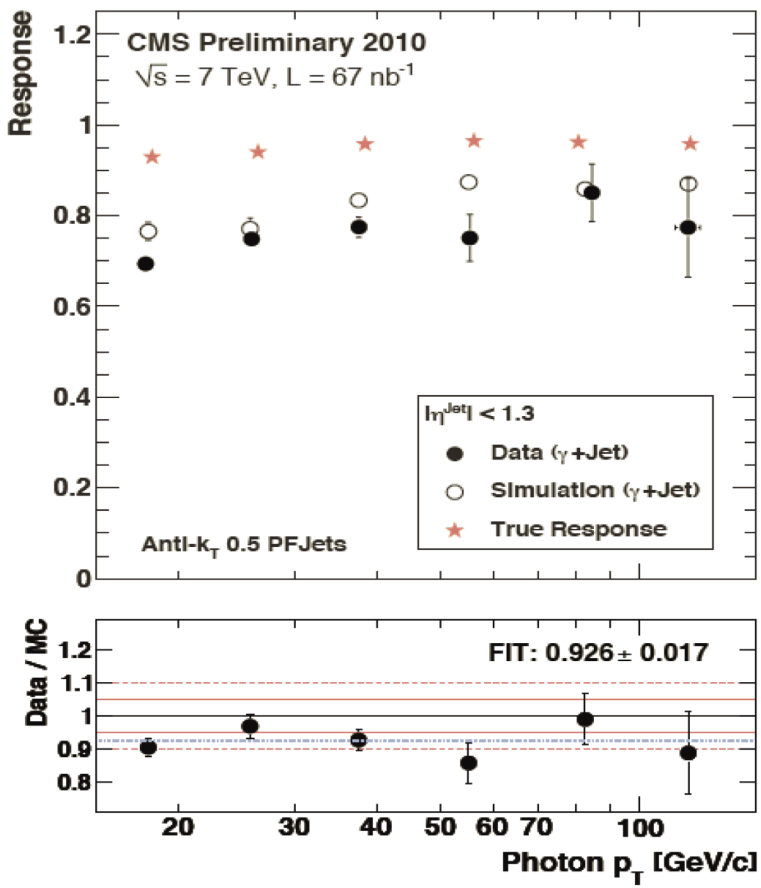




Jet energy calibration

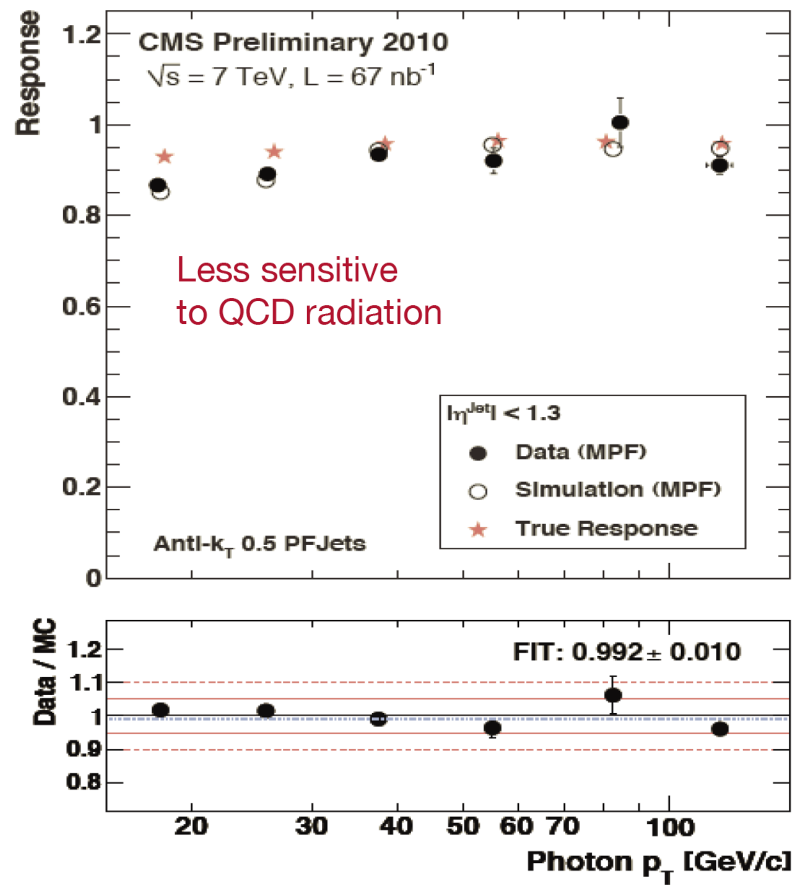
Simple Photon+jet balance

Bias due to soft veto on second jet

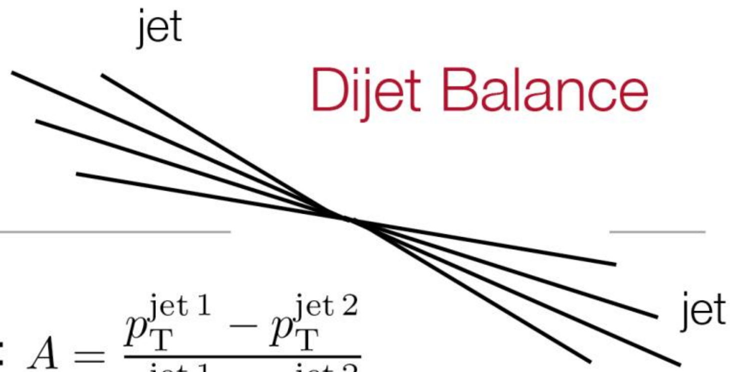


MET projection fraction method

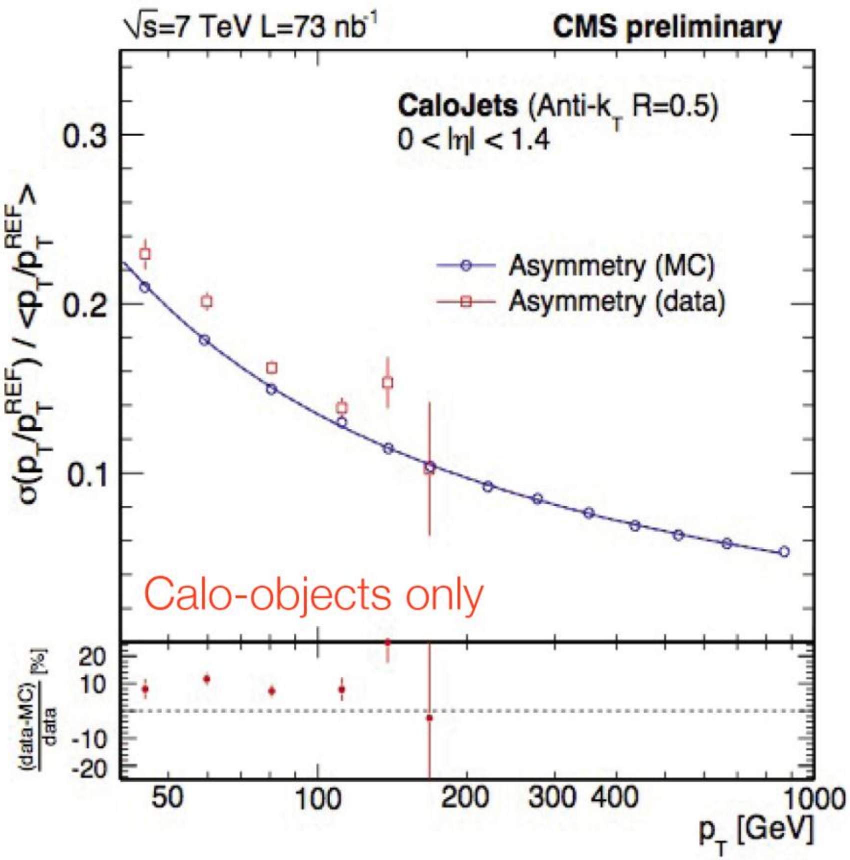
Sums over non-photon E_T for balance

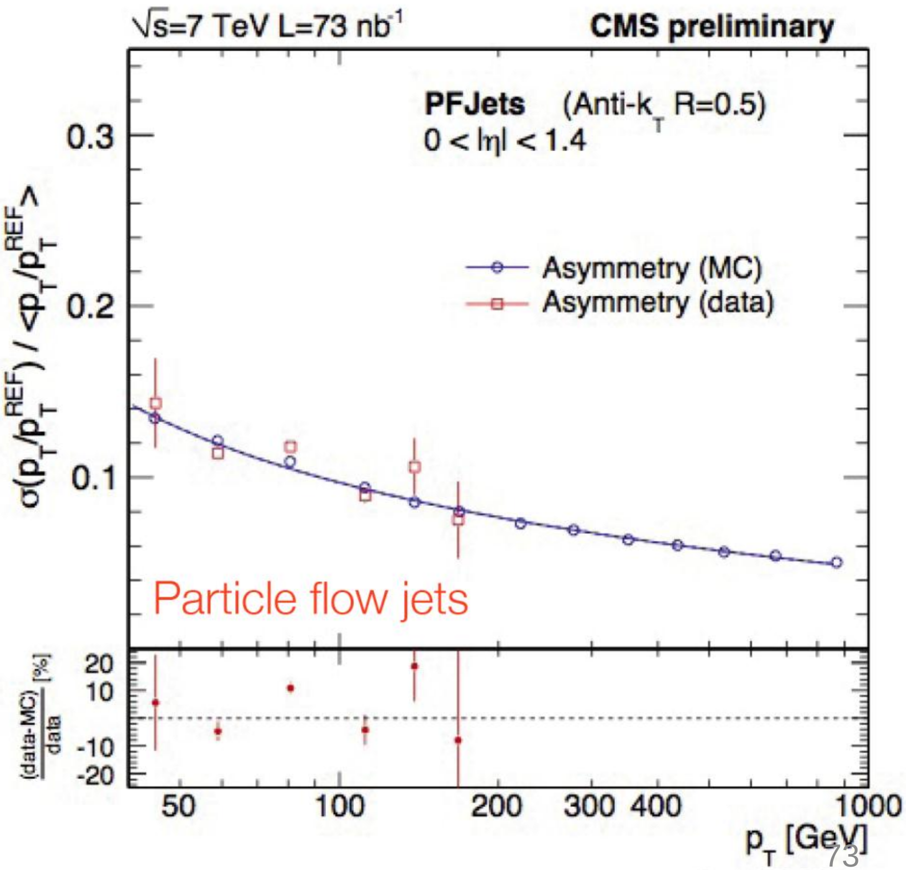


Jet energy resolution



Resolution: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$ using p_T asymmetry: $A = \frac{p_T^{\text{jet 1}} - p_T^{\text{jet 2}}}{p_T^{\text{jet 1}} + p_T^{\text{jet 2}}}$



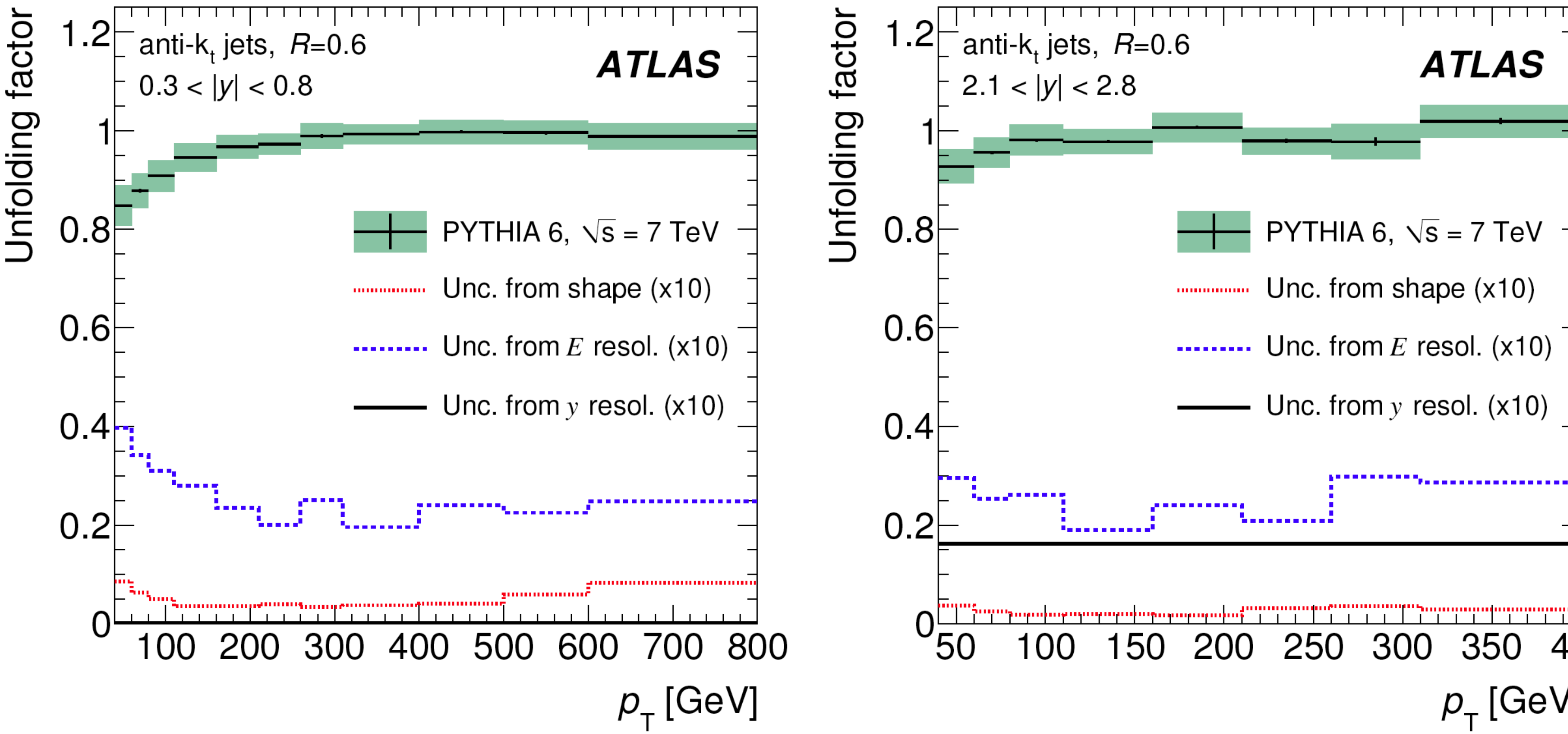


Resolution unfolding

['bin-by-bin' unfolding]

$$N_{\text{part}} = N_{\text{meas}} \cdot \frac{N_{\text{part}}^{\text{MC}}}{N_{\text{meas}}^{\text{MC}}}$$

Measured spectrum =
Real spectrum ⊗ Experim. resolution



[ATLAS Collaboration; arXiv:1009.5908v2; Fig. 8]

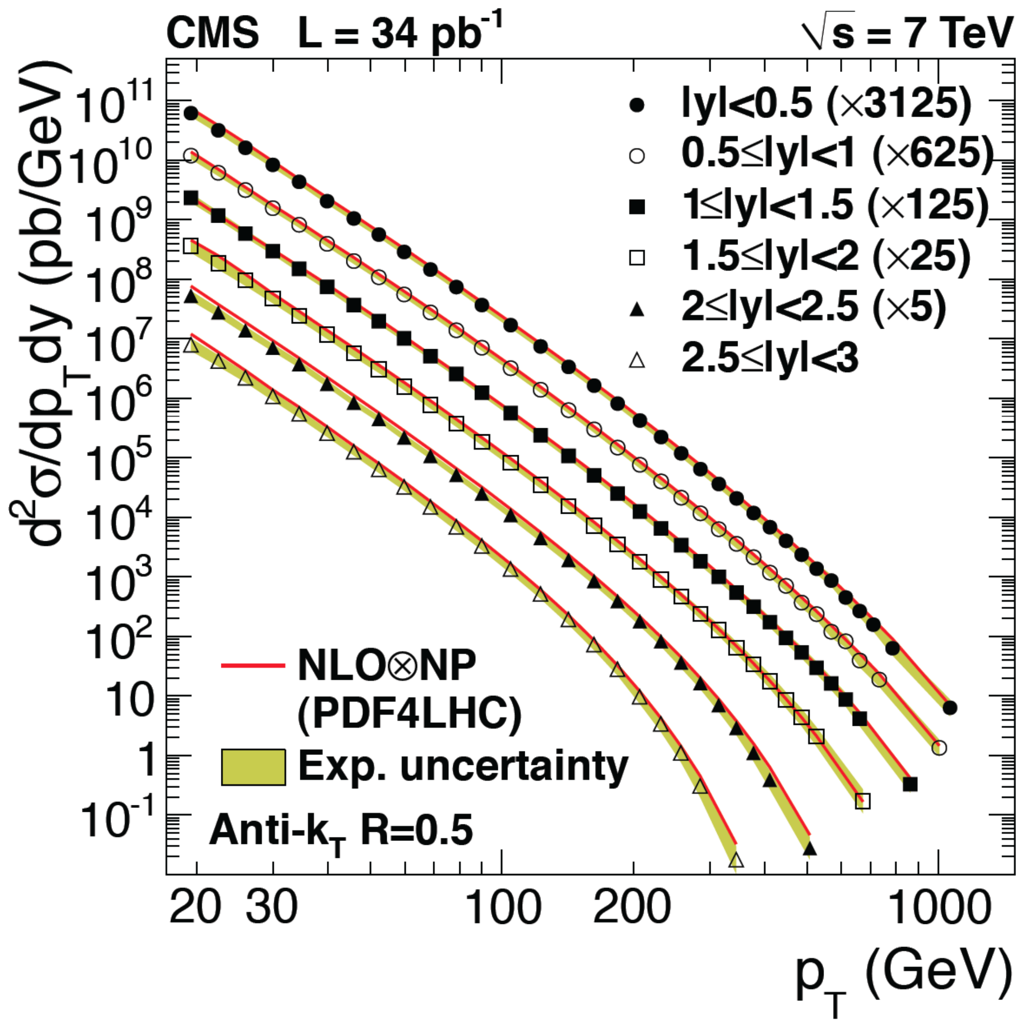
Inclusive jet cross-section

Cross section is huge
(~ Tevatron x 100)

Very good agreement with NLO QCD over nine orders of magnitude

PT extending from 20 to 500 GeV

Main uncertainty:
Jet Energy Scale (3-4%)



Inclusive jet cross-section

[ATLAS Collaboration; arXiv:1009.5908v2; Tab. 1]

$0 < \|y\| < 0.3$									
p_T [GeV]	60-80	80-110	110-160	160-210	210-260	260-310	310-400	400-500	500-600
Measured cross section [pb/GeV]	3.5e+04	7.9e+03	1.4e+03	2.7e+02	43	22	8.8	2.0	–

NLO p

0.3 <

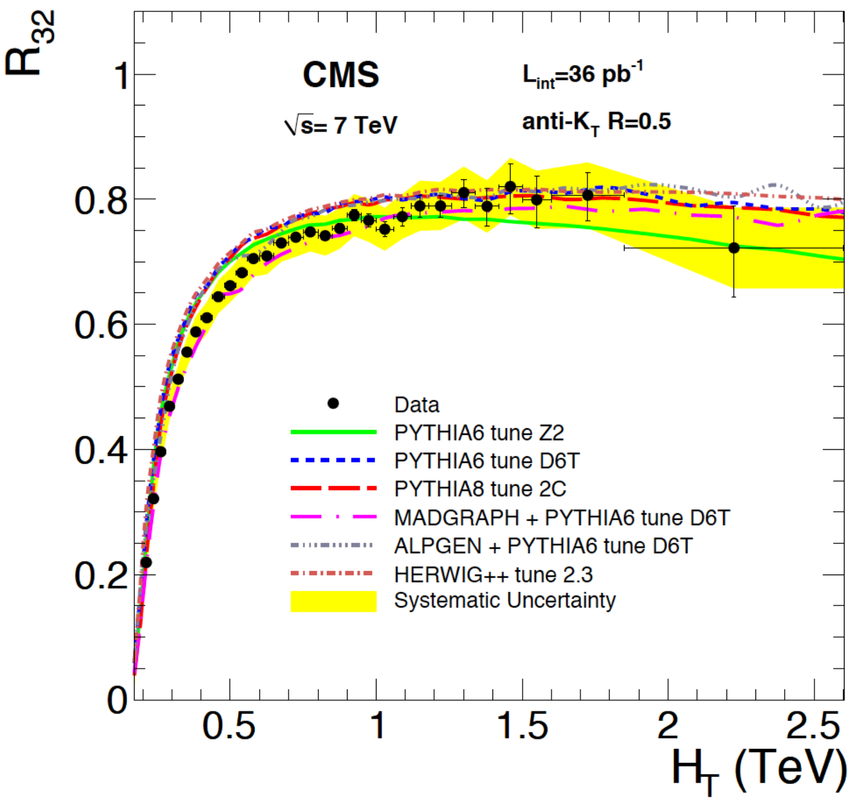
NLO p

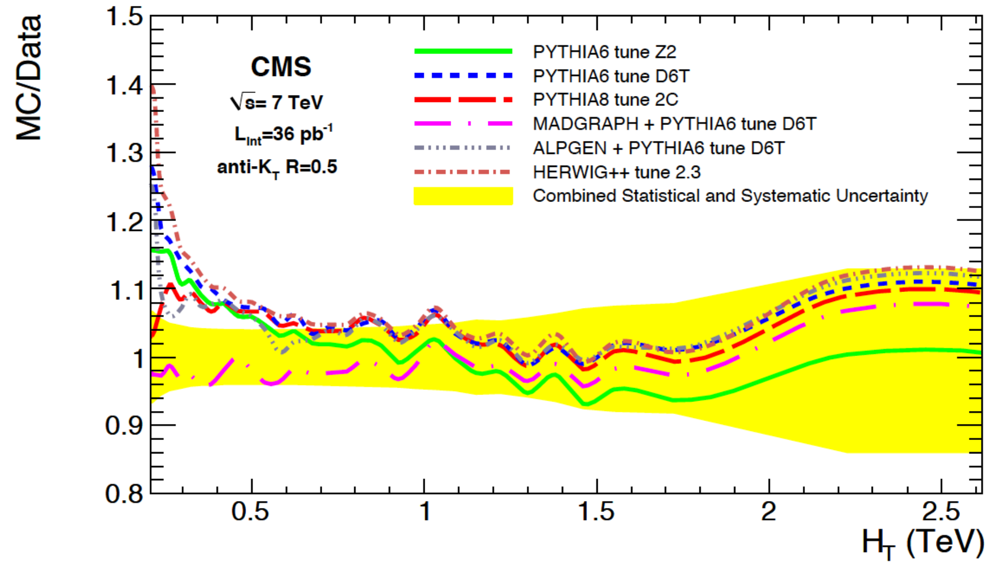
Table
pQCD
the me
where

$0 < \|y\| < 0.3$	
p_T [GeV]	60-80
Measured cross section [pb/GeV]	3.5e+04
NLO pQCD (CTEQ 6.6) × non-pert. corr. [pb/GeV]	4.1e+04
Non-perturbative correction	0.92
Statistical uncertainty	0.011
Absolute JES uncertainty	$^{+0.25}_{-0.22}$
Unfolding uncertainty	0.04
Total systematic uncertainty	$^{+0.3}_{-0.2}$
PDF uncertainty	0.02
Scale uncertainty	$^{+0.006}_{-0.04}$
α_s uncertainty	0.03
Non-perturbative correction uncertainty	$^{+0.06}_{-0}$
Total theory uncertainty	$^{+0.07}_{-0.05}$

Inclusive jet cross sections: 3-jet / 2-jet ratio

hep-ex 1106.0647, PLB 702 (2011) 336



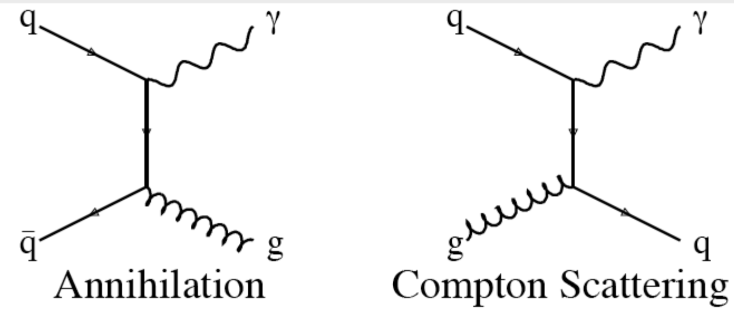


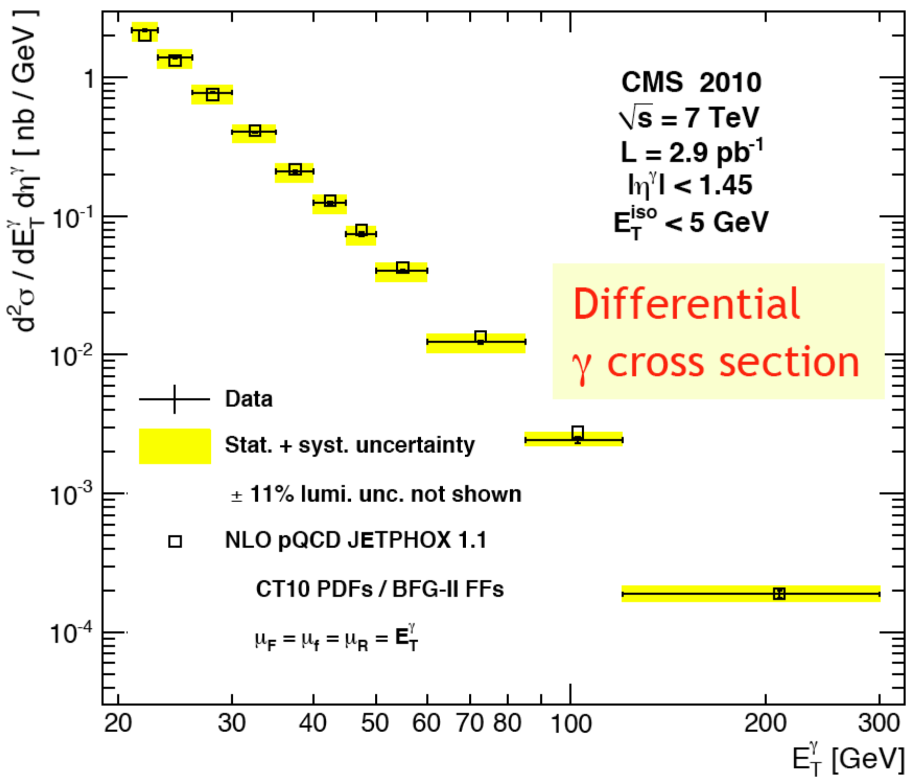
$$H_T = \sum_{i=1}^{N} p_{T\,i}$$

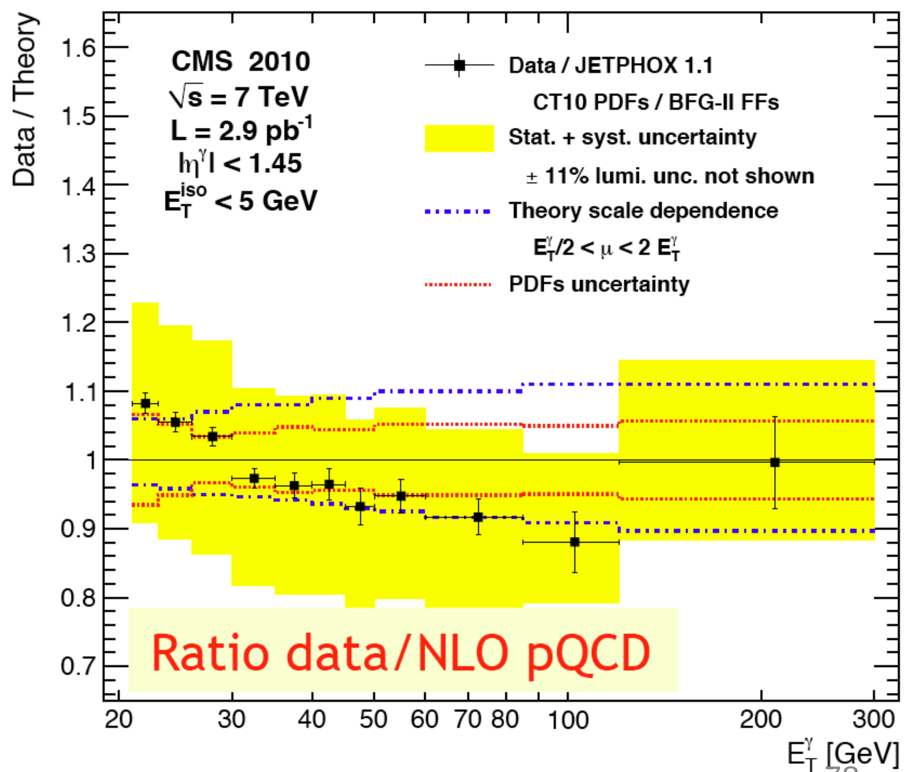
Direct photon production

hep-ex 1012.0799 (Dec. 2010)

Precision test of perturbative QCD
Constrain PDF in the proton
Background for e.g. H→γγ

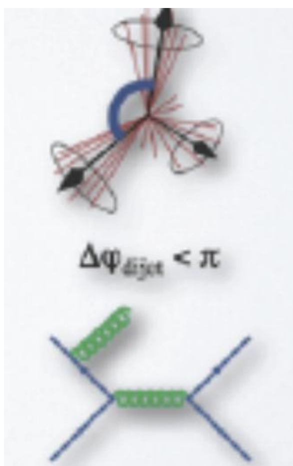


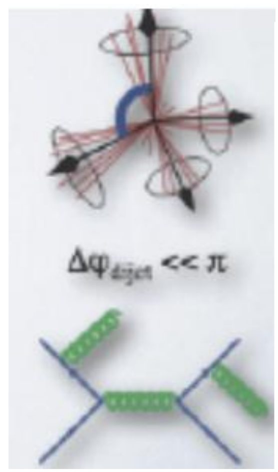


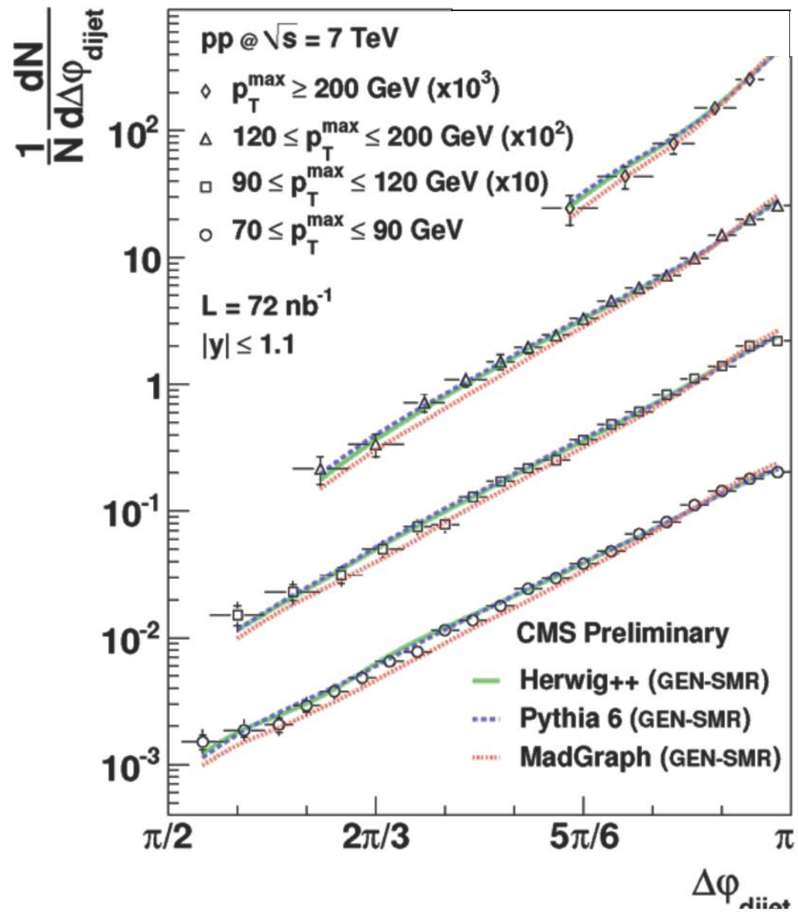


Jets: angular correlations

Difference in azimuth of the two leading jets
Probe of QCD high-order processes
Very slight dependence on JES
No dependence on luminosity







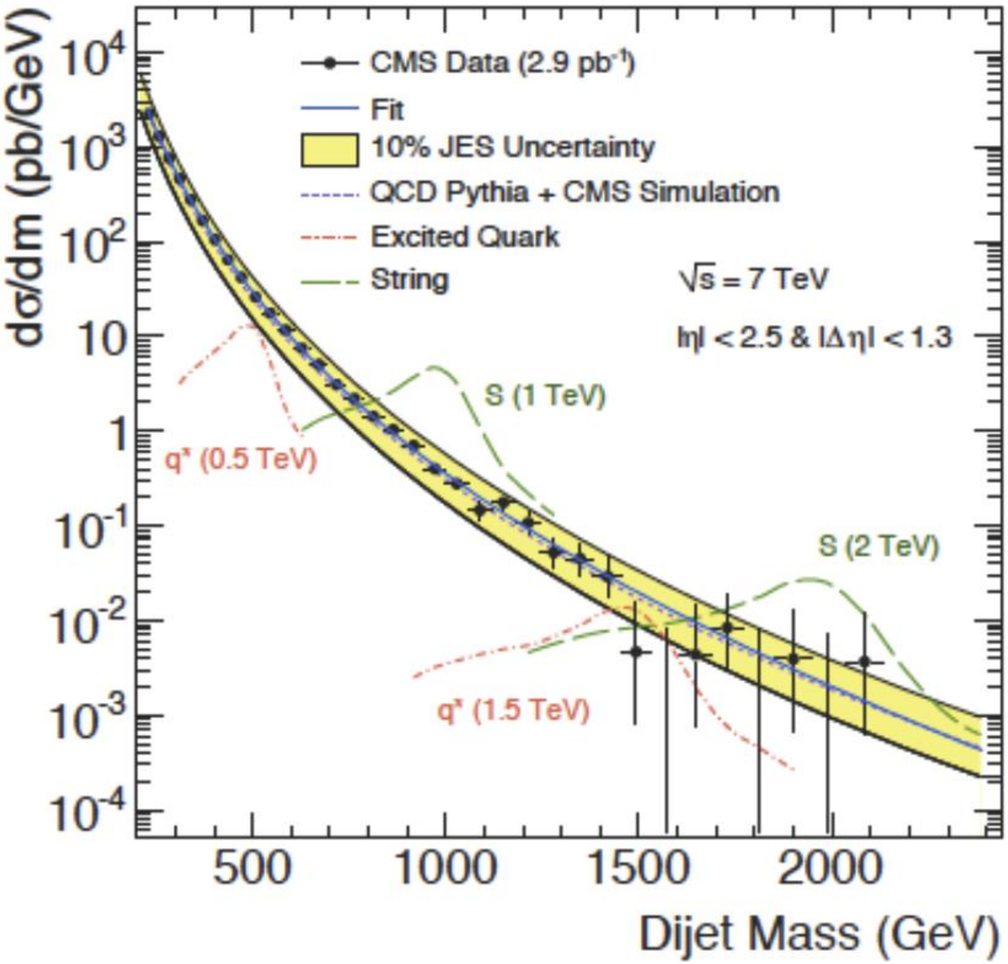
Dijet mass

Very early search for numerous resonances BSM:
string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons

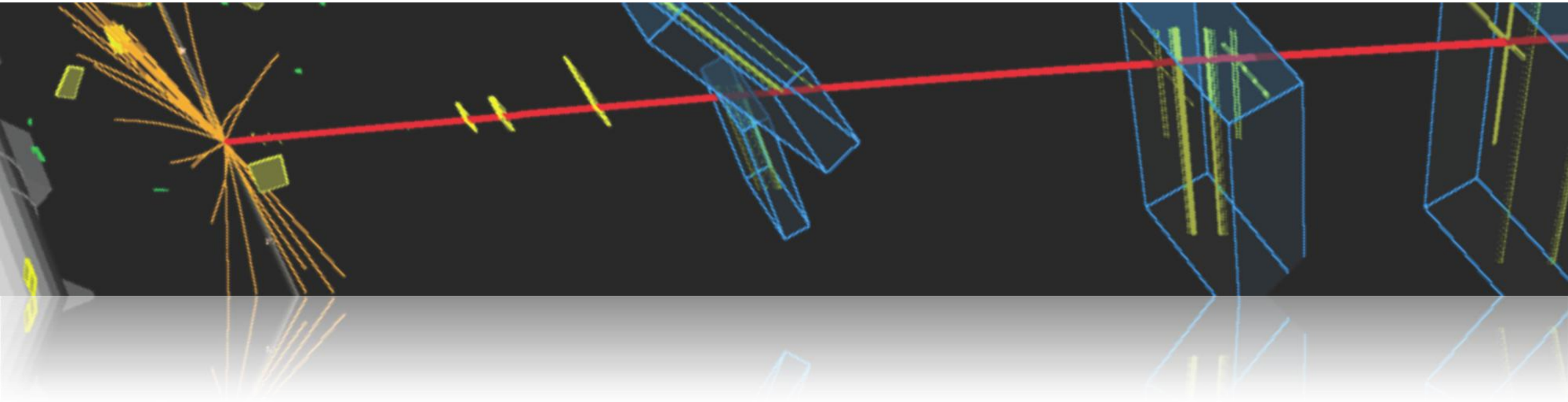
Four-parameter fit to describe QCD shape:

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^{B}};$$

$$B = p_2 + p_3\left(m/\sqrt{s}\right)$$

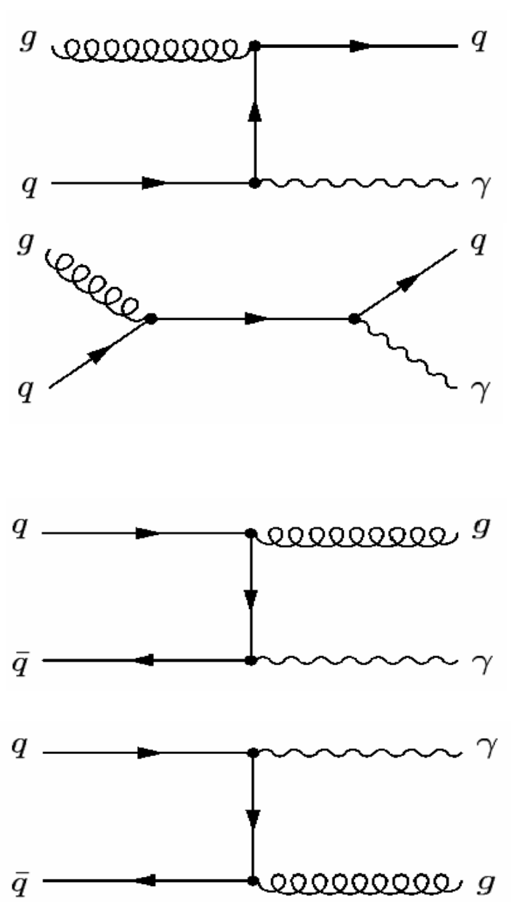


W and Z bosons

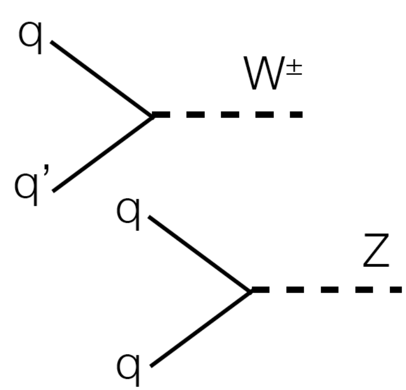


Vector boson production

Direct γ-production:



Singel W/Z production:



W production: (main contributions) $\begin{cases} u\bar{d} \rightarrow W^{+} \\ d\bar{u} \rightarrow W^{-} \end{cases}$

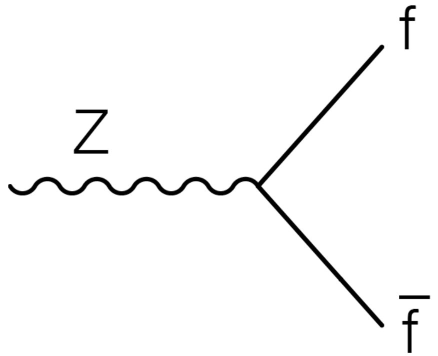
Z production: (main contributions) $\begin{cases} u\bar{u} \rightarrow Z \\ d\bar{d} \rightarrow Z \end{cases}$

- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

➥ Constraints on sea and gluon distributions

Z-boson interaction

$$\text{"}ffZ\text{"} : e(s_W c_W)^{-1}(\mathbf{T}_3 - \sin^2\theta_W \mathbf{Q})$$



NC interaction:

$$\mathcal{L}_{\text{int}}^{Z} = -e(s_W c_W)^{-1}\mathbf{Z}_\mu \;\bar{\psi}\,\gamma^\mu(\mathbf{T}_3 - s_W^2\mathbf{Q})\psi$$

$$= -e(s_W c_W)^{-1}\mathbf{Z}_\mu \;\bar{\psi}\,\gamma^\mu[\,1/2(1-\gamma^5)\mathbf{T}_3 - s_W^2\mathbf{Q}\,]\,\psi$$

$$= -g/c_W \cdot \mathbf{Z}_\mu \cdot 1/2 \cdot (\;\bar{\psi}\,\gamma^\mu[\,\mathbf{T}_3 - 2s_W^2\mathbf{Q}\,]\psi - \;\bar{\psi}\,\gamma^\mu\gamma^5\,\mathbf{T}_3\,\psi)$$

propagator

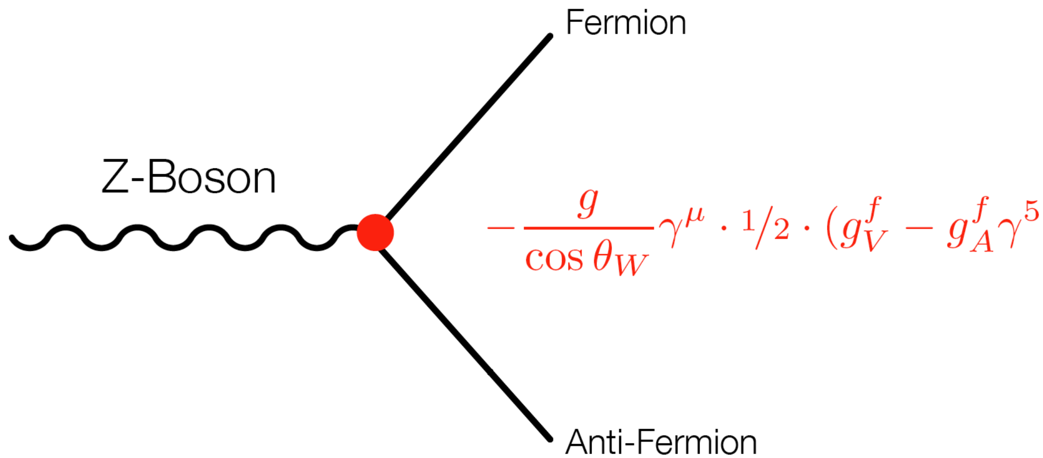
vector coupling

axial coupling

$$\mathcal{L}_{\text{int}}^{Z} = -g/c_W \cdot \mathbf{Z}_\mu \cdot 1/2 \cdot (\;\bar{\psi}\,\gamma^\mu g_V\,\psi - \;\bar{\psi}\,\gamma^\mu\gamma^5 g_A\,\psi)$$

Z-boson interaction

Couplings
to the Z-Boson:



$g_V = T_3 - 2Q\sin^2\theta_W$
$g_A = T_3$

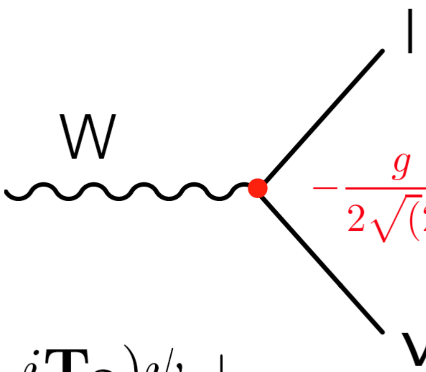
Standard Model	g_V	g_A
ν	$1/2$	$1/2$
ℓ^-	$-1/2 + 2\sin^2\theta_W$	$-1/2$
$u-quark$	$+1/2 - 4/3\sin^2\theta_W$	$1/2$
$d-quark$	$-1/2 + 2/3\sin^2\theta_W$	$-1/2$

Couplings to
left/right handed fermions:

$g_L = ½(g_V+g_A)$
$g_R = ½(g_V-g_A)$

W-boson interaction

$$"\ell\nu W", "udW" : e(\sqrt{2}s_W)^{-1}$$



$$-\frac{g}{2\sqrt{(2)}} \cdot \gamma^\mu \cdot (1-\gamma^5)$$

CC interaction:
[e,ν only]

$$\mathcal{L}^W_{\text{int}} = -e(\sqrt{2}s_W)^{-1}\left[\mathbf{W}^+_\mu\ \bar{\psi}\gamma^\mu(\mathbf{T_1}+i\mathbf{T_2})\psi + \right.$$

$$\left. + \mathbf{W}^-_\mu\ \bar{\psi}\gamma^\mu(\mathbf{T_1}-i\mathbf{T_2})\psi\right]$$

$$= -{}^{e}/\sqrt{2}s_W \left[\mathbf{W}^+_\mu\ (\bar{\nu}_e)_L\gamma^\mu e_L + \mathbf{W}^-_\mu\ \bar{e}_L\gamma^\mu(\nu_e)_L\right]$$

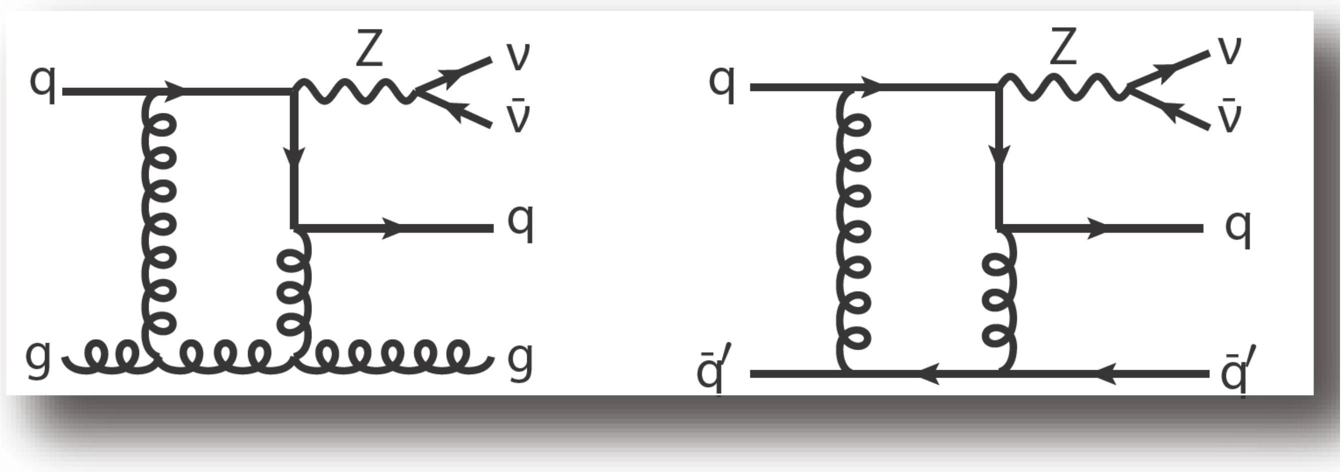
propagator

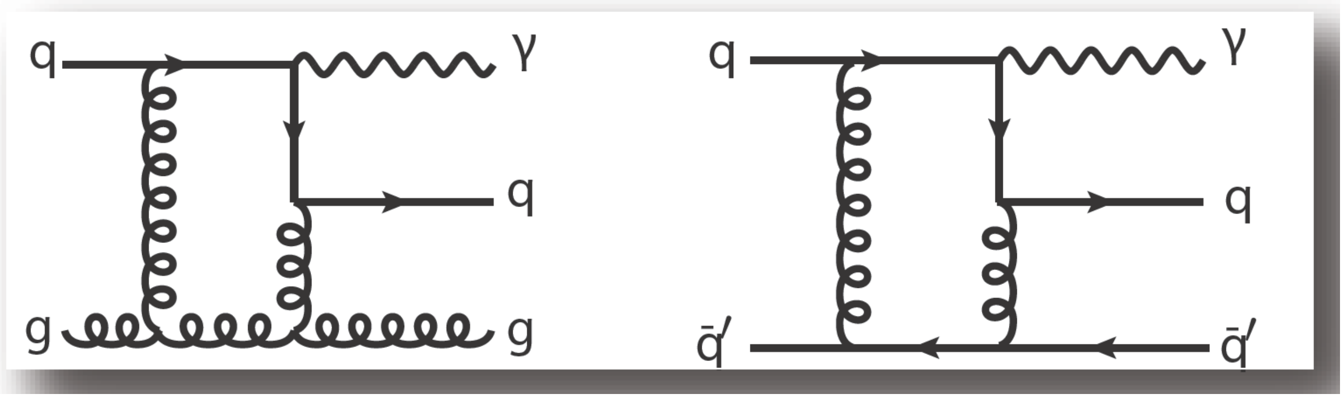
left-handed

$$\boxed{\mathcal{L}^W_{\text{int}} = -{}^{g}/\sqrt{2}\left[\mathbf{W}^+_\mu\ (\bar{\nu}_e)_L\gamma^\mu e_L + \mathbf{W}^-_\mu\ \bar{e}_L\gamma^\mu(\nu_e)_L\right]}$$

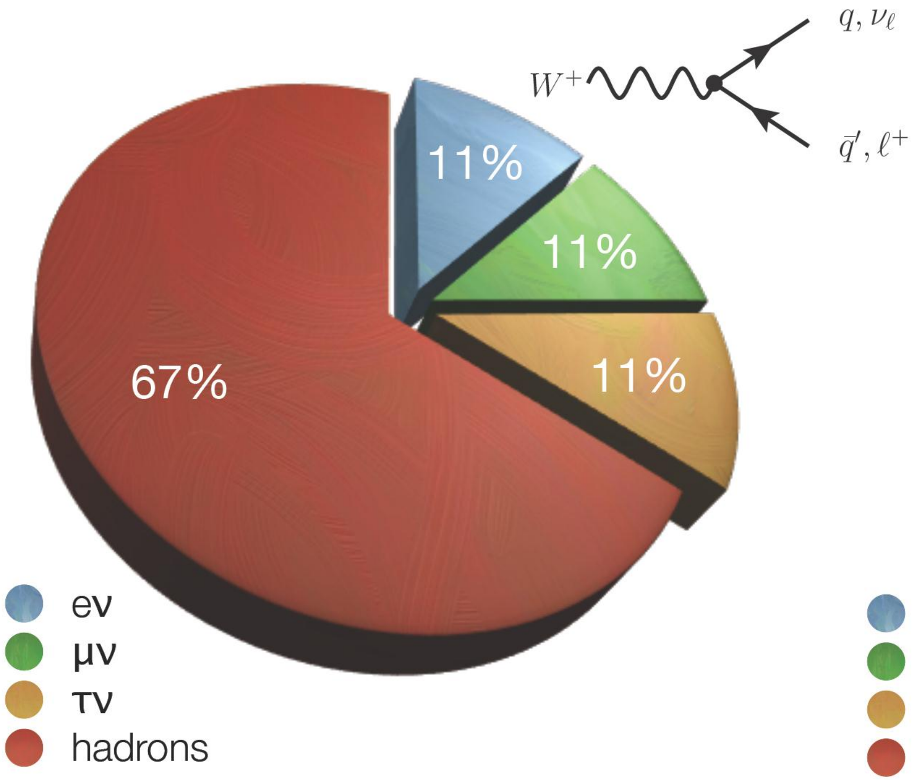
Fermions with
$T \neq 0$ only

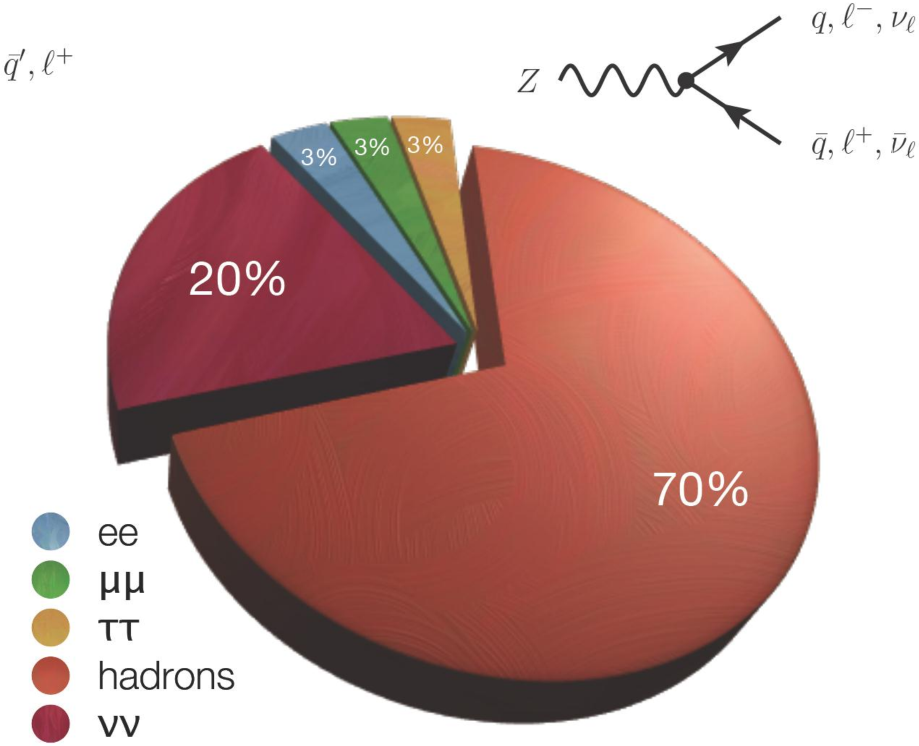
Examples of high-order processes





W and Z boson decays

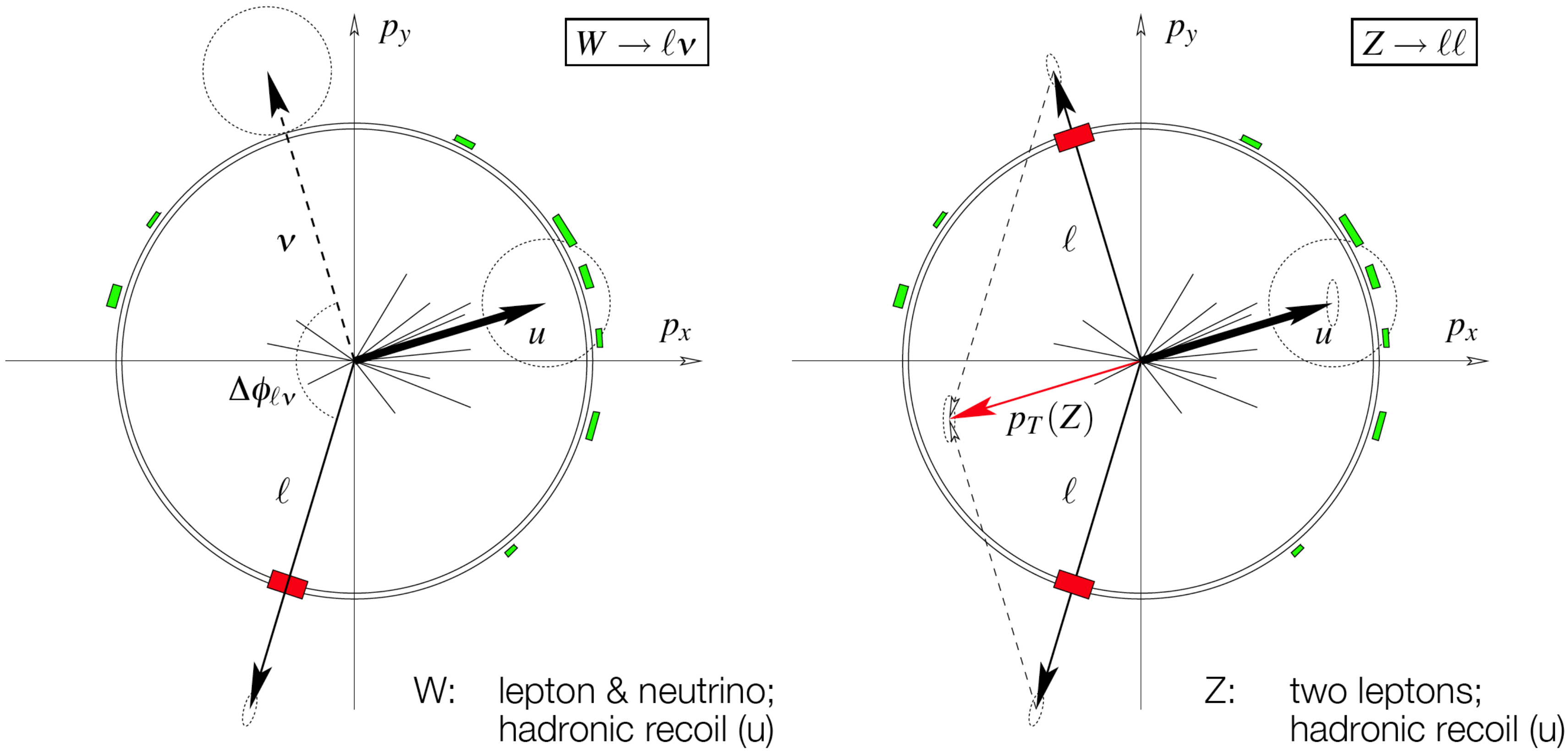




Leptonic decays (e/μ): very clean, but small(ish) branching fractions
Hadronic decays: two-jet final states; large QCD dijet background
Tau decays: somewhere in between…

W and Z boson signatures

[CERN-OPEN-2008-020]



Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

Isolated High-p_T Leptons

Starting point for many hadron collider analyses:
isolated high-p_T leptons ➛ discriminate against QCD jets ...

QCD jets can be mis-reconstructed
as leptons (“fake leptons”)

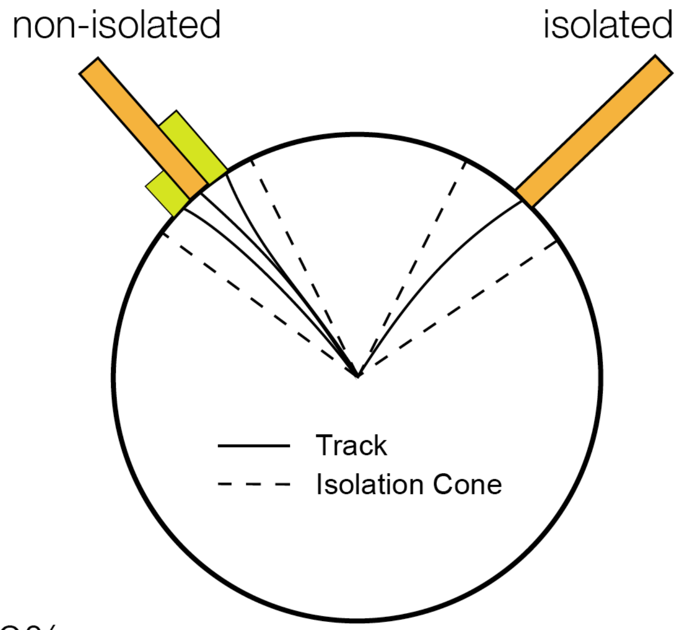
QCD jets may contain real leptons
e.g. from semileptonic B decays [$B \to l\nu X$]

➛ soft and surrounded by other particles

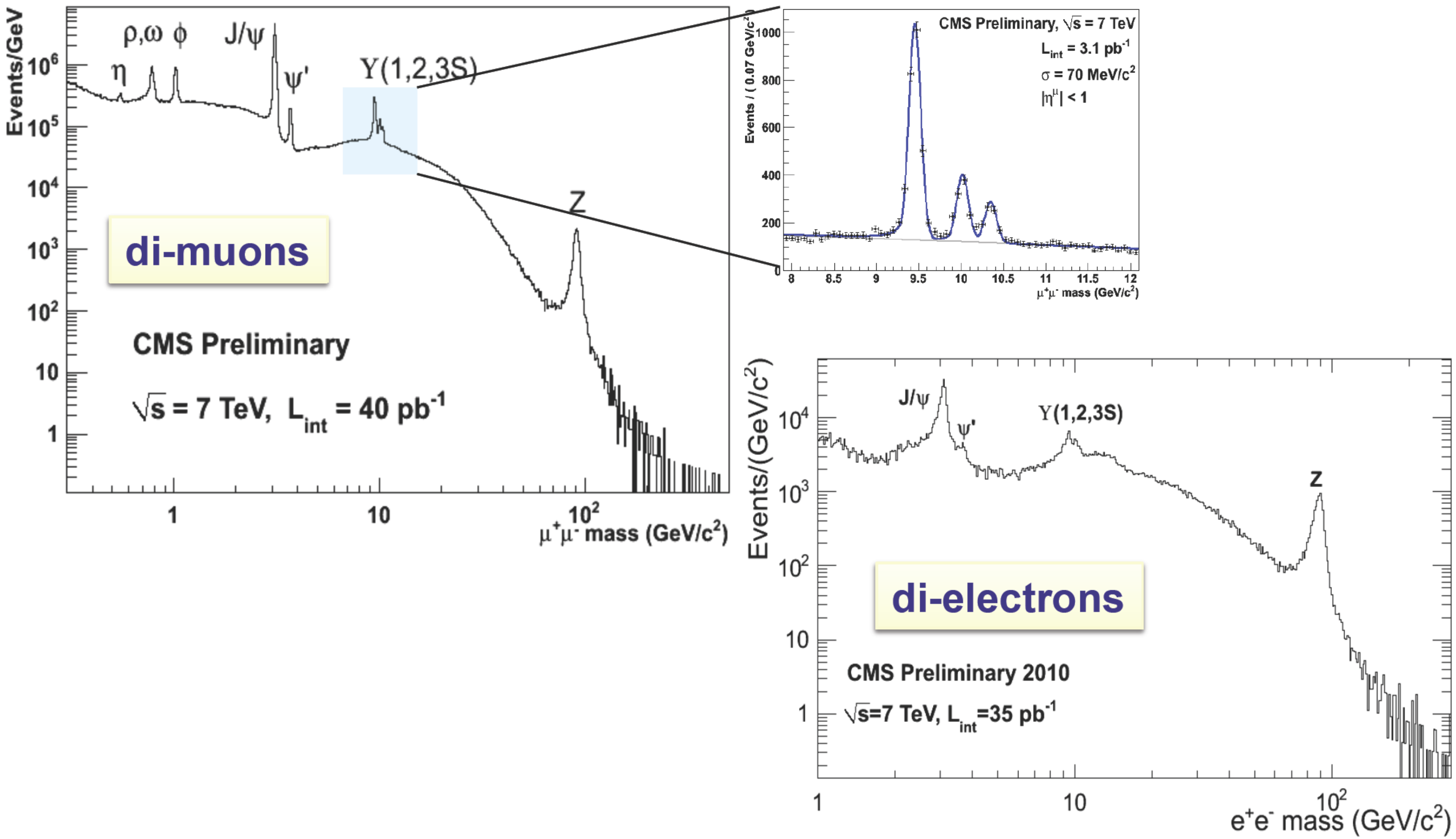
“Tight” lepton selection ...

Require e/μ with $p_T >$ (at least) 20 GeV
Track isolation, e.g. $\sum p_T$ of other tracks
in cone of ΔR=0.1 less than 10% of lepton p_T

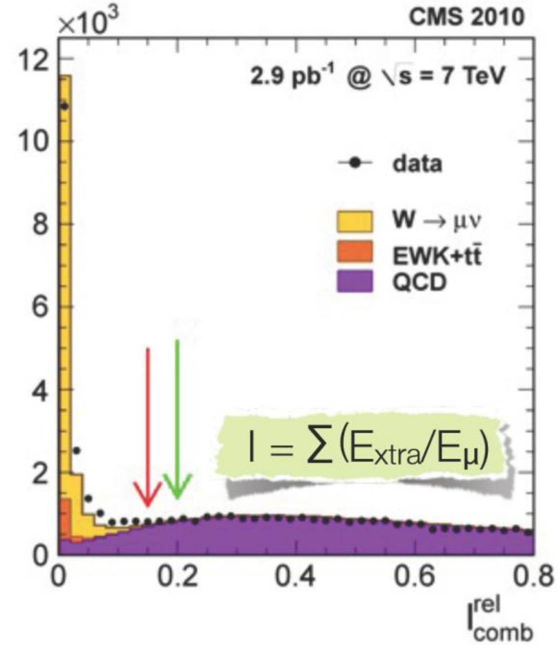
Calorimeter isolation, e.g. energy deposition
from other particles in cone of ΔR=0.2 less than 10%



Dilepton mass spectrum at 7 TeV

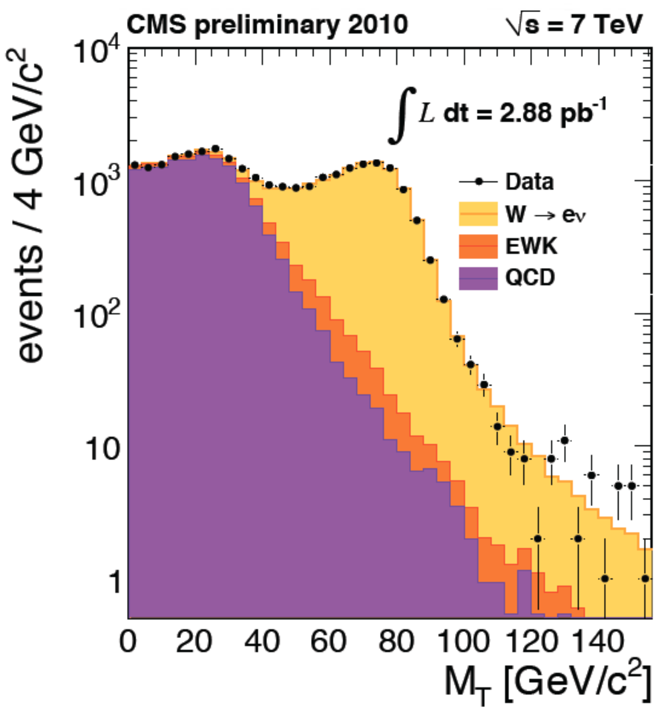


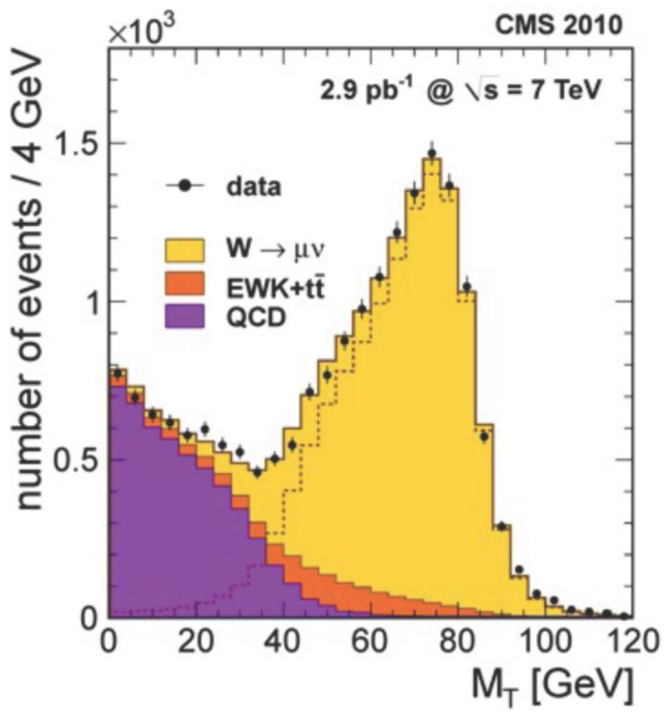
Example: CMS W Analysis



Select isolated electrons and muons ...
[muons: p_T>9 GeV; electrons: p_T>20 GeV]

Investigate transverse mass ...
[Use $E_{T,miss}$; $M_T = (p_{lep} + E_{T,miss})^{½}$]

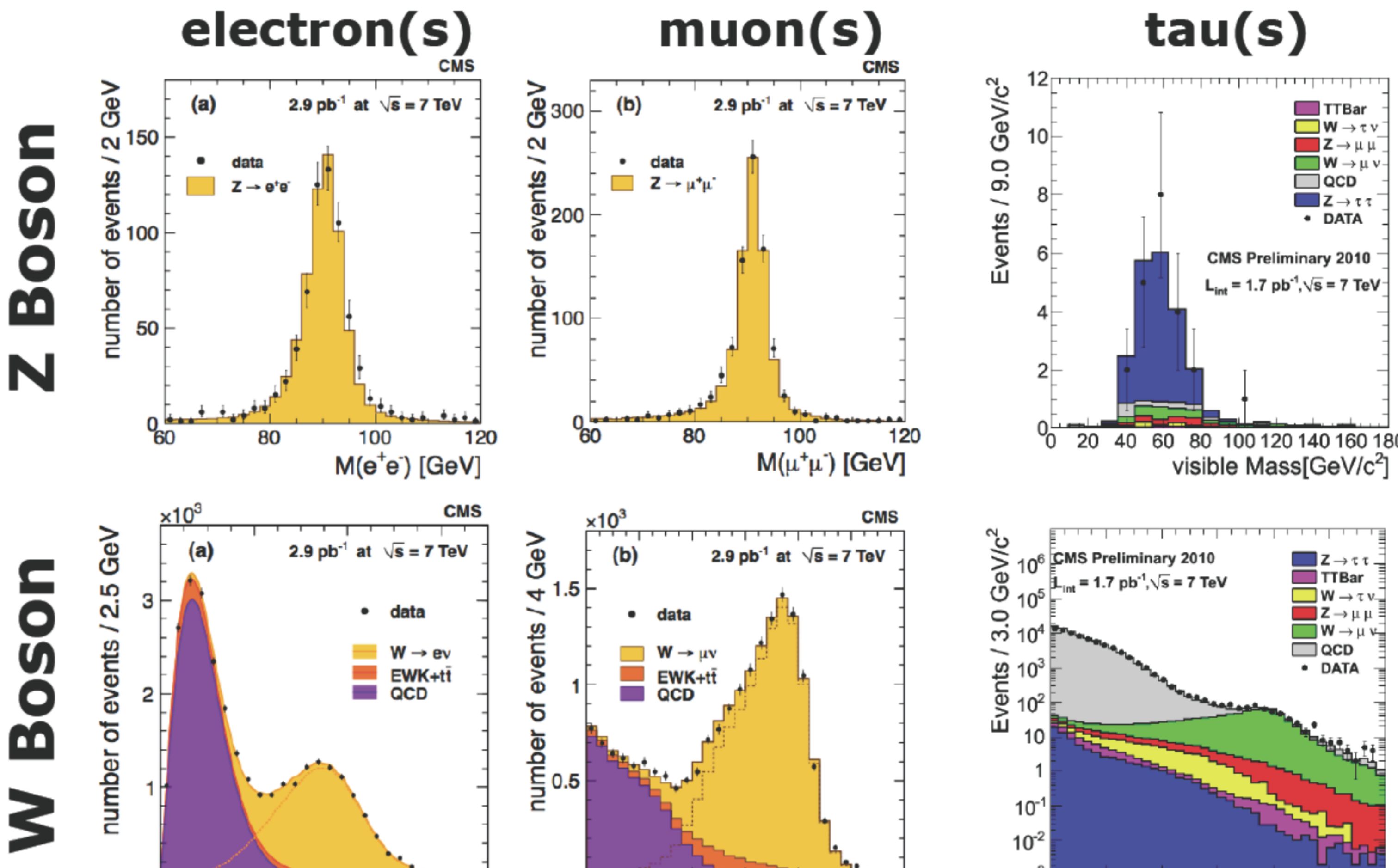




The W signal yield is extracted from a binned likelihood fit to the M_T distribution. Three different contributions:

- W signal
- QCD background
- other (EWK) backgrounds.

W/Z production at 7 TeV

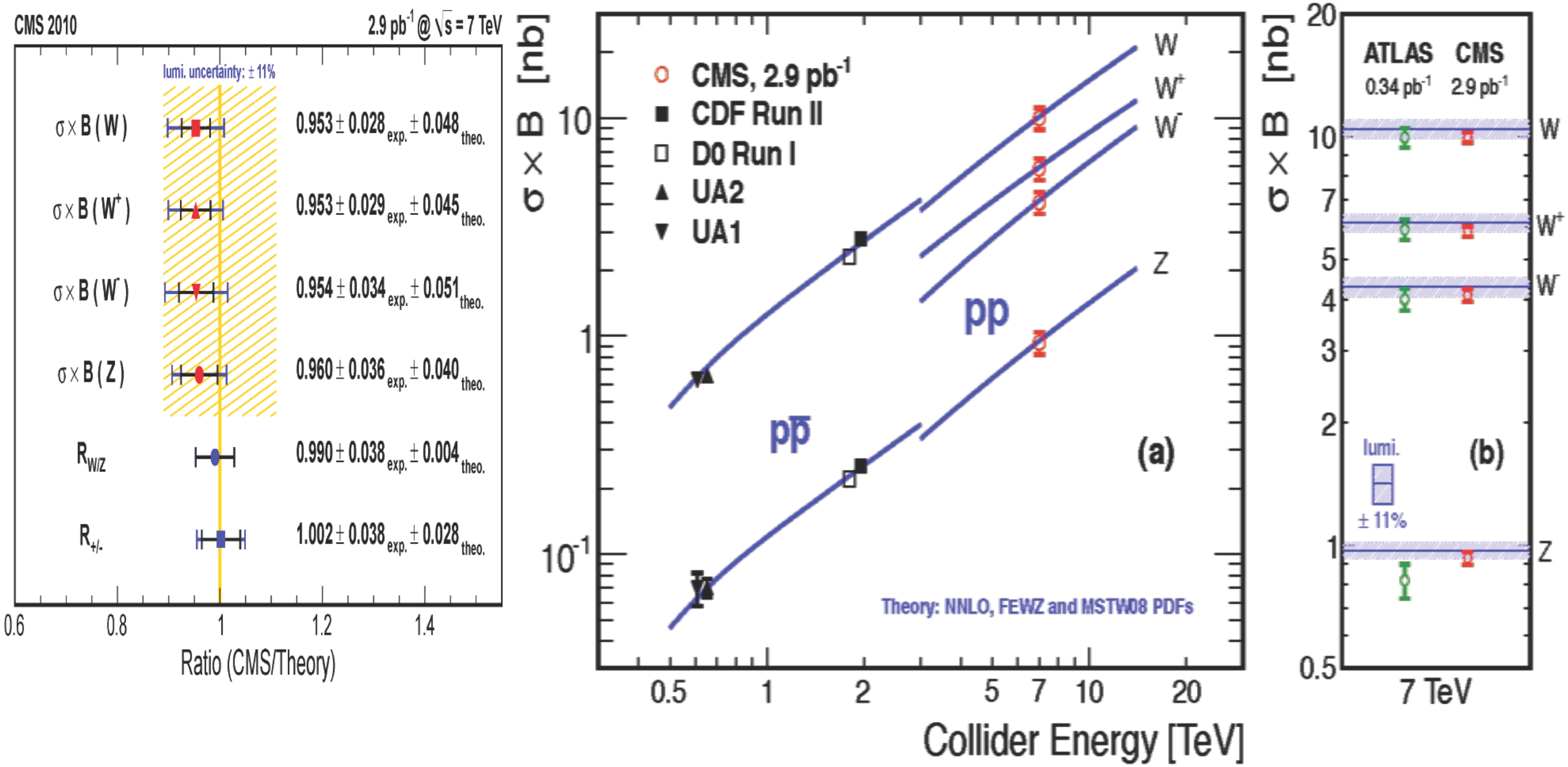


Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}}$$

W, Z cross-section v.s. √s

hep-ex 1012.2466, JHEP 01 (2011) 080



W+/W- charge asymmetry

NNLO cross sections:
scale uncertainties very small

W rapidity: asymmetry
[sensitivity to PDFs]

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

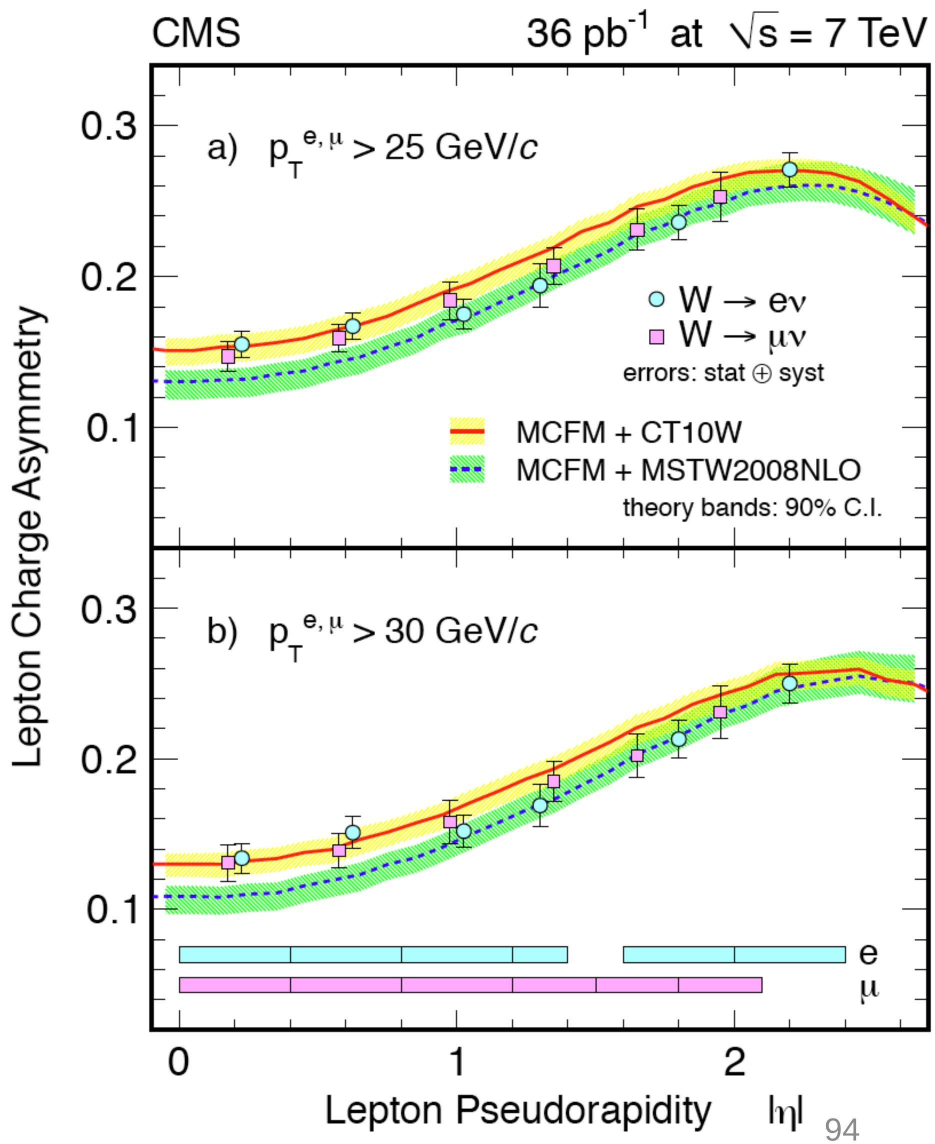
Proton-Proton Collider:

symmetry around y=0 ...

PDFs:

u(x) > d(x) for large x ...
more W^+ at positive rapidity

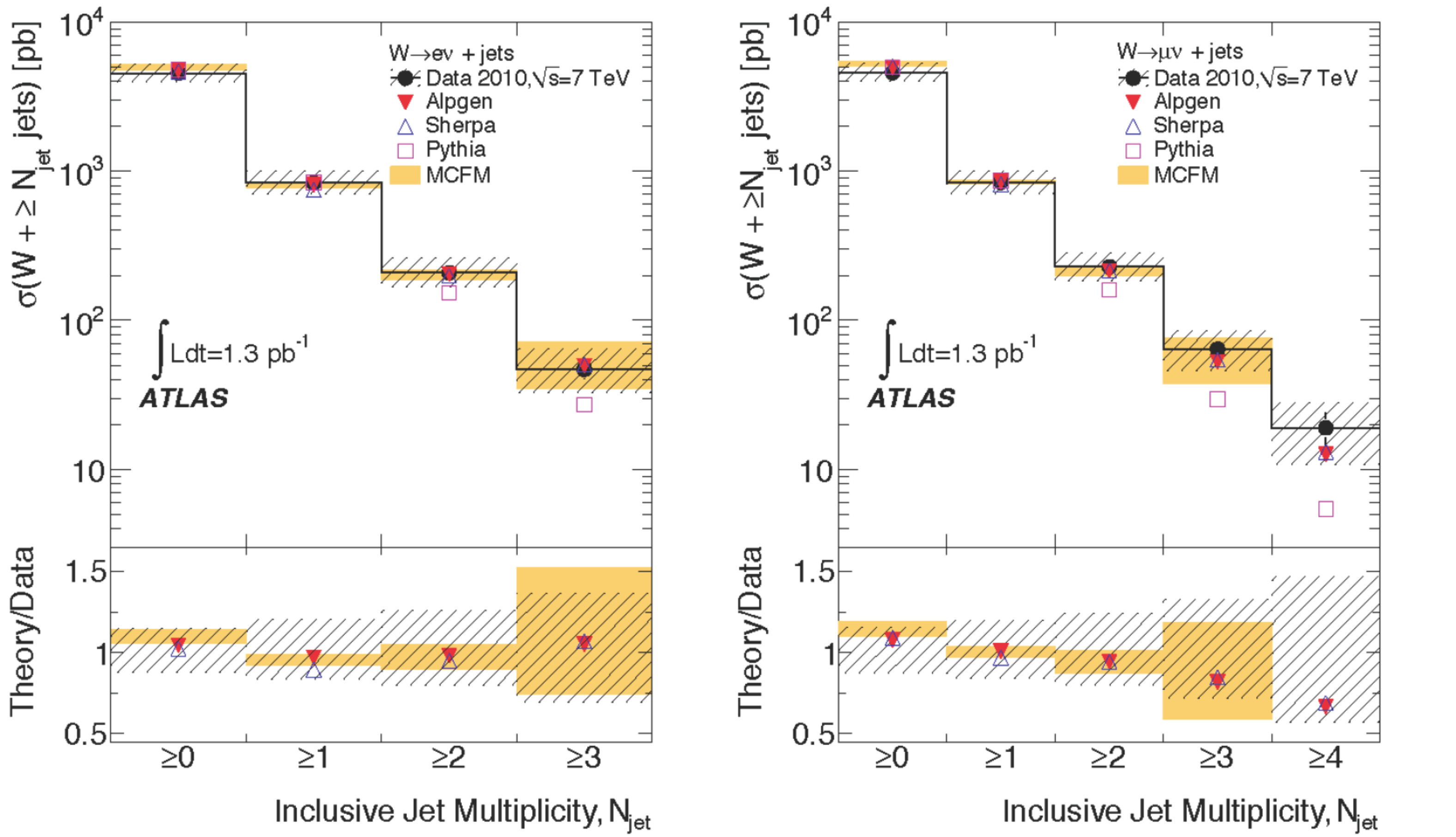
d/u ratio < 1 ...
always more W^+ than W^-



W + Jets multiplicity

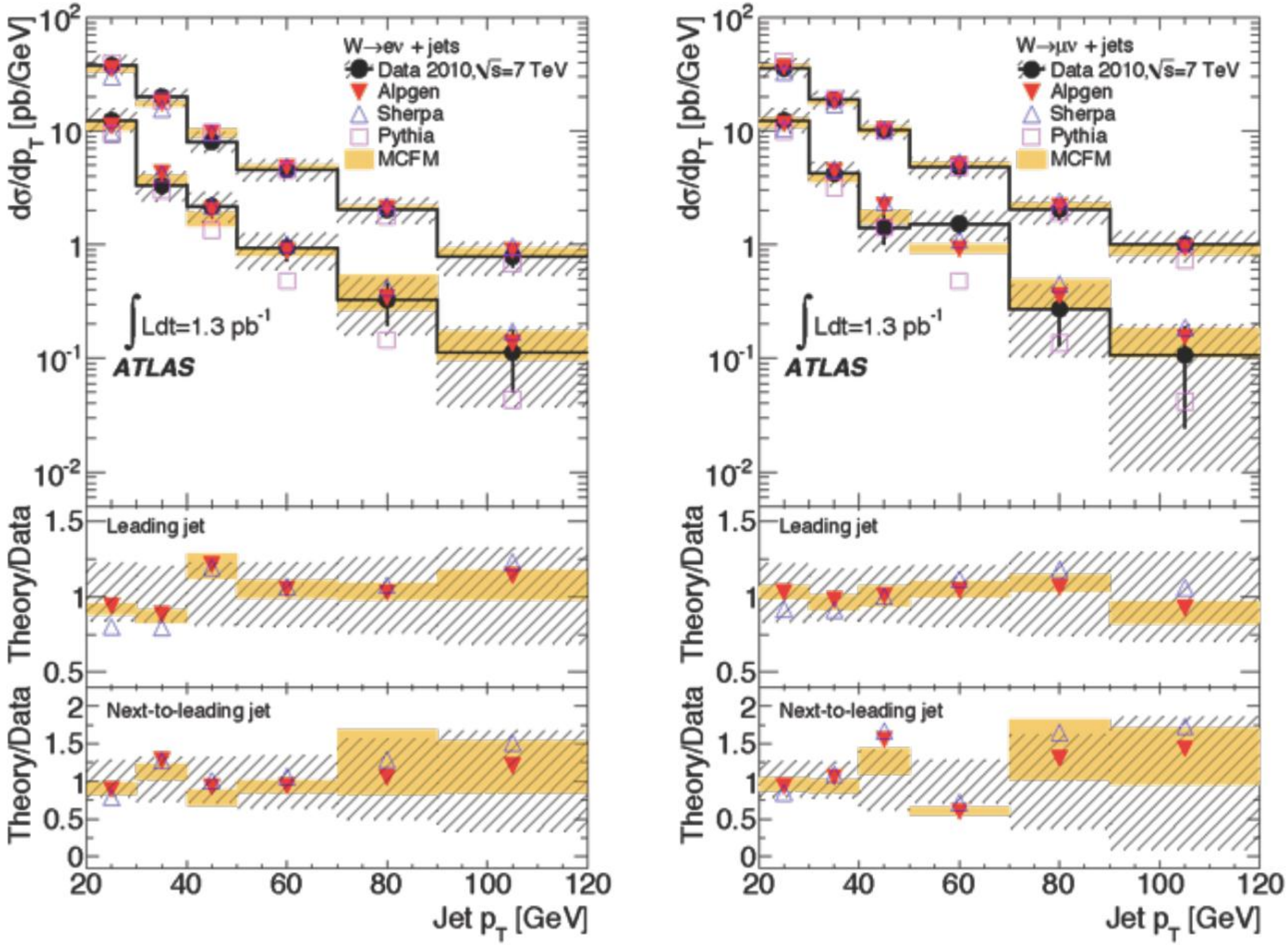
$|\eta| < 2.8$ and $p_T > 20$ GeV

arXiv:1012.5382

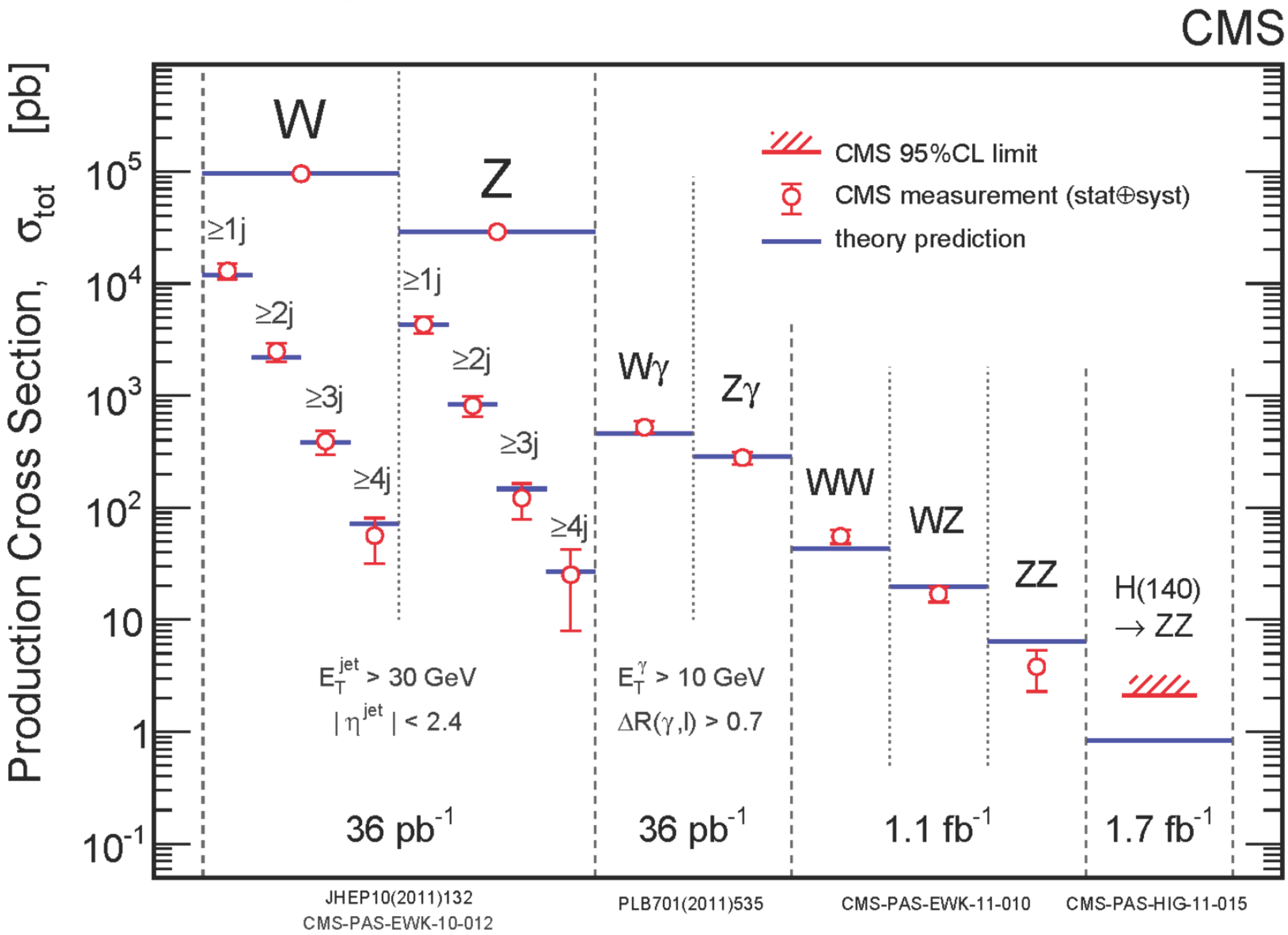


W + Jets P_T

Tails are important in several Exotica and SUSY searches



SM processes measured at LHC



W Mass Determination

Very challenging measurement

Template method:

Fit templates (from MC simulation) with different m_W to data

➛ W mass from best fit

Requires very good modeling of physics & detector

Present systematic uncertainties:
[DØ-Experiment]

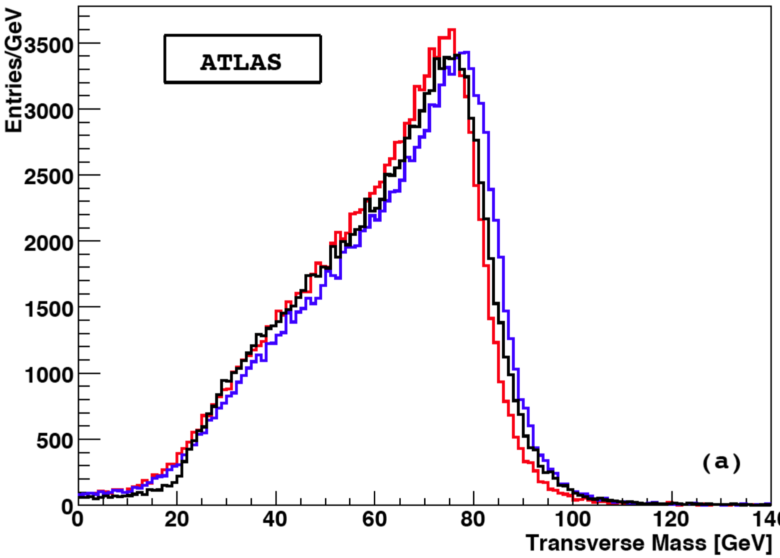
Lepton energy scale: 34 MeV

➛ calibrated to known Z mass
[calorimeter: 3.6% for 50 GeV]

Hadronic recoil: 6 MeV

W production model [PDFs, ...]: 12 MeV

Templates for
$m_W = 80.4 \pm 1.6$ GeV



[CERN-OPEN-2008-020]

Ultimate LHC goal:
m_W uncertainty of 15 MeV
[via combination]

Acknowledgments

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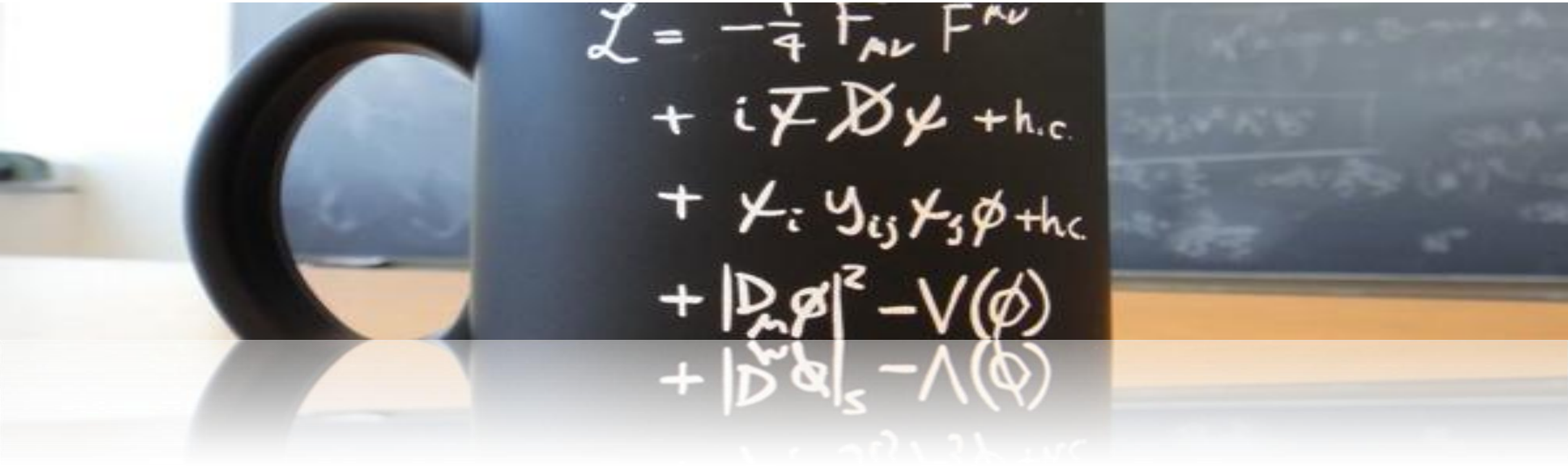
Hans-Christian Schultz-Coulon
Kirchhoff-Institut fur Physic

for allowing to use material of the course
Advanced Topics in Particle Physics
University of Heidelberg

End of Lecture 3

Electroweak theory (reminder)



Electroweak Theory

Unified theory of electromagnetic and weak interactions

Non-abelian gauge group: $SU(2)_T \times U(1)_Y$
[T: weak isospin ➛ coupling g, Y: hypercharge ➛ coupling g']

Pure Yang-Mills theory:
Massless gauge bosons $W^{1,2,3}$, B^0

Electroweak symmetry breaking:
Masses for gauge bosons and fermions [Higgs mechanism]

Three generations of quarks and leptons

$T = ½$

Left-handed doublets: $\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L, \quad \begin{pmatrix}u\\ d\end{pmatrix}_L, \begin{pmatrix}c\\ s\end{pmatrix}_L, \begin{pmatrix}t\\ b\end{pmatrix}_L$

Right-handed singlets: $e_R, \quad \mu_R, \quad \tau_R, \quad u_R, d_R, \; c_R, s_R, \; t_R, b_R$

$T = 0$

Rich flavor phenomenology ...

Electroweak Theory

W and Z masses: connected via weak mixing angle

$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{v^2}{4}(g^2 + g'^2) \quad \rightarrow \quad \frac{m_W^2}{m_Z^2 \cos\theta_W} = 1$$

g : SU(2)$_T$ coupling
g' : U(1)$_Y$ coupling
θ_W : Weinberg angle
v : vacuum expectation value

Couplings to W and Z
[here: leptons only]

$$\mathcal{L}^{CC} = -\frac{g}{\sqrt{2}}\left[J_\mu^{+CC} W^{\mu,-} + J_\mu^{-CC} W^{\mu,+}\right]$$

$$= -\frac{g}{\sqrt{2}}\left[\left(\bar{\nu}_e \gamma_\mu \frac{1}{2}(1-\gamma_5) e\right) W^{\mu,-} + \left(\bar{e}\gamma_\mu \frac{1}{2}(1-\gamma_5)\nu_e\right) W^{\mu,+}\right]$$

Charged current: always flavor-changing
[quarks: mass eigenstates ≠ EW eigenstates → CKM matrix]

$$\mathcal{L}^{NC} = -\frac{g}{2\cos\theta_W} J_\mu^{NC} Z^\mu$$

$$= -\frac{g}{2\cos\theta_W}\left[\bar{\nu}_e\gamma_\mu \frac{1}{2}(1-\gamma_5)\nu_e - \bar{e}\gamma_\mu \frac{1}{2}(1-\gamma_5) e + 2\sin^2\theta_W (\bar{e}\gamma_\mu e)\right] Z^\mu$$

Neutral current: always flavor-conserving

The SM Lagrangian

Free Fields

Interaction

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}'$$

Gauge Bosons

$$\mathcal{L}_0 = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu\partial_\mu\psi$$

Fermions

$$\mathcal{L}' = e\bar{\psi}\gamma^\mu A_\mu\psi$$

Fermion-Boson
Coupling

$$eA_\mu = \frac{g_s}{2}\lambda_\nu G^\nu_\mu + \frac{g}{2}\vec{\tau}\,\vec{W}_\mu + \frac{g'}{2}YB_\mu$$

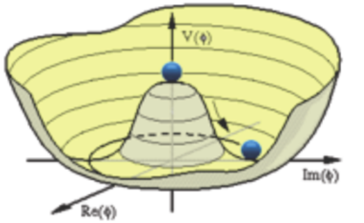
$$F_{\mu\nu}F^{\mu\nu} = G_{\mu\nu}G^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} + B_{\mu\nu}B^{\mu\nu}$$

The Higgs mechanism

Yukawa Couplings

Higgs Field

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}' + \mathcal{L}_{\text{Yuk}} + \mathcal{L}_{\phi'}$$



$$\mathcal{L}_\phi = (\partial_\mu \phi^\dagger)(\partial^\mu \phi) - V(\phi)$$

Higgs Potential

$$\mathcal{L}_{\text{Yuk}} = c_f(\bar{\psi}_L \psi_R \phi + \bar{\psi}_R \psi_L \phi)$$

Higgs Fermion Interaction

Gauge Boson masses: $i\partial_\mu \to i(\partial_\mu - ieA_\mu)$

Fermion masses: $c_f \bar{\psi}\psi\phi$

and $\phi' = \phi - \rho_0$

Vacuum expectation value

SM parameters

3 Couplings	$g_s,\ e,\ \sin\theta_W$
4 CKM parameters	$\vartheta_1,\ \vartheta_2,\ \vartheta_3,\ \delta$
2 Boson masses	$m_{\mathrm{Z}},\ m_{\mathrm{H}}$
3 Lepton masses	$m_{\mathrm{e}},\ m_{\mu},\ m_{\tau}$
6 Quark masses	$m_{\mathrm{u}},\ m_{\mathrm{d}},\ m_{\mathrm{s}},\ m_{\mathrm{c}},\ m_{\mathrm{t}},\ m_{\mathrm{b}}\,.$

18 free SM parameters
no neutrino masses

$$
\begin{aligned}
m_{\mathrm{W}}^2 &= \tfrac{1}{2}\, g^2\, \rho_0^2 \\
m_{\mathrm{Z}}^2 &= \tfrac{1}{2}\, (g^2 + g'^2)\, \rho_0^2 \\
m_{\mathrm{H}}^2 &= 4\, \lambda \rho_0^2
\end{aligned}
$$

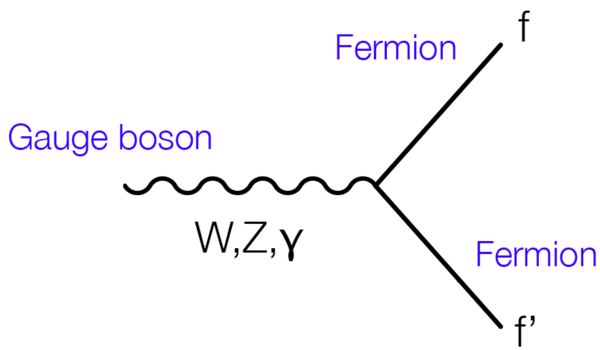
$$
\begin{aligned}
g &= e/\sin\theta_W \\
g' &= e/\cos\theta_W
\end{aligned}
$$

$$m_f = c_f\, \rho_0$$

Fermion-Boson Interaction

$$i\,\bar{\psi}\gamma^{\mu}\mathbf{D}_{\mu}\psi$$

Fermion-Boson Interaction



$$= i\,\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi + \mathcal{L}_{\text{int}}$$

using

$$\mathbf{D}_{\mu} = \partial_{\mu} + ig\mathbf{W}_{\mu}^{a}\mathbf{T}^{a} + ig'\mathbf{B}_{\mu}\mathbf{Y}$$

$$\mathcal{L}_{\text{int}} = -\bar{\psi}\gamma^{\mu}(g\mathbf{W}_{\mu}^{a}\mathbf{T}^{a} + g'\mathbf{B}_{\mu}\mathbf{Y})\psi$$

Weak Isospin

Hypercharge

Fermion-Boson Interaction

$$\mathcal{L}_{\rm int} = -\bar{\psi}\gamma^{\mu}(g\mathbf{W}^{a}_{\mu}\mathbf{T}^{a} + g'\mathbf{B}_{\mu}\mathbf{Y})\psi$$

with a = 1,2,3

$$\mathbf{W}^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(\mathbf{W}^{1}_{\mu} \mp i\mathbf{W}^{2}_{\mu})$$

$$\mathbf{A}_{\mu} = \frac{1}{\sqrt{g^2+g'^2}}(g\mathbf{W}^{3}_{\mu} + g'\mathbf{B}_{\mu}) = \mathbf{W}^{3}_{\mu}\cos\theta_W + \mathbf{B}_{\mu}\sin\theta_W$$

Weinberg angle θ_W

$$\mathbf{Z}_{\mu} = \frac{1}{\sqrt{g^2+g'^2}}(g\mathbf{W}^{3}_{\mu} - g'\mathbf{B}_{\mu}) = \mathbf{W}^{3}_{\mu}\cos\theta_W - \mathbf{B}_{\mu}\sin\theta_W$$

$$\begin{aligned} s_W &= \sin\theta_W \\ c_W &= \cos\theta_W \\ e &= g\sin\theta_W \\ &= g'\cos\theta_W \end{aligned}$$

$$\mathcal{L}_{\rm int} = -e\left[\,\mathbf{A}_{\mu}\mathcal{J}^{\mu}_{\rm em} + (s_W c_W)^{-1}\mathbf{Z}_{\mu}\mathcal{J}^{\mu}_{\rm NC} + (\sqrt{2}s_W)^{-1}(\mathbf{W}^{+}_{\mu}\mathcal{J}^{\mu}_{\rm CC} + \mathbf{W}^{-}_{\mu}\mathcal{J}^{\mu\dagger}_{\rm CC})\,\right]$$

e.m. current

neutral current

charged current

Fermion-Boson Interaction

$$\mathcal{L}_{\text{int}} = -e\,[\,\mathbf{A}_\mu \mathcal{J}^\mu_{\text{em}} + (s_W c_W)^{-1}\mathbf{Z}_\mu \mathcal{J}^\mu_{\text{NC}}$$
$$+(\sqrt{2}s_W)^{-1}(\mathbf{W}^+_\mu \mathcal{J}^\mu_{\text{CC}} + \mathbf{W}^-_\mu \mathcal{J}^{\mu\dagger}_{\text{CC}})\,]$$

$$\mathcal{J}^\mu_{\text{em}} = \bar\psi\gamma^\mu(\mathbf{T}_3 + \mathbf{Y})\psi = \bar\psi\gamma^\mu\mathbf{Q}\psi$$

charge

3rd isospin component

$$\mathcal{J}^\mu_{\text{NC}} = \bar\psi\gamma^\mu(\mathbf{T}_3 - \sin^2\theta_W(\mathbf{T}_3 + \mathbf{Y}))\psi = \bar\psi\gamma^\mu(\mathbf{T}_3 - \sin^2\theta_W\mathbf{Q})\psi$$

$$\mathcal{J}^\mu_{\text{CC}} = \bar\psi\gamma^\mu(\mathbf{T}_1 + i\mathbf{T}_2)\psi$$

isospin raising operator

Coupling strengths:

$$\text{"}ff\gamma\text{"}: e\mathbf{Q} \qquad \text{"}ffZ\text{"}: e(s_W c_W)^{-1}(\mathbf{T}_3 - \sin^2\theta_W\mathbf{Q})$$

$$\text{"}\ell\nu W\text{"}, \text{"}udW\text{"}: e(\sqrt{2}s_W)^{-1}$$

[left-handed only]

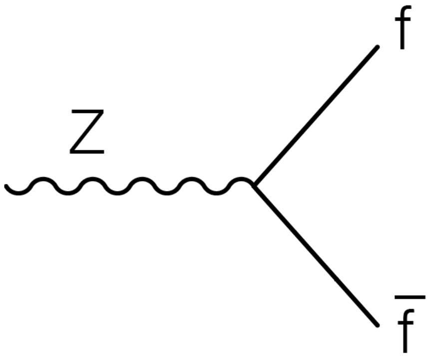
Flavor Quantum Numbers

			T	T_3	Y	Q
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1/2 1/2	1/2 – 1/2	– 1/2 – 1/2	0 – 1
e_R	μ_R	τ_R	0	0	– 1	– 1
$\begin{pmatrix} u_L \\ d'_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s'_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b'_L \end{pmatrix}$	1/2 1/2	1/2 – 1/2	1/6 1/6	2/3 – 1/3
u_R d_R	c_R s_R	t_R b_R	0 0	0 0	2/3 – 1/3	2/3 - 1/3

T : Weak Isospin
T_3 : 3rd Isospin Component
Y : Hypercharge
Q : Charge [=T_3-Y]

Z-boson interaction

$$\text{"}ffZ\text{"} : e(s_W c_W)^{-1}(\mathbf{T}_3 - \sin^2\theta_W \mathbf{Q})$$



NC interaction:

$$\mathcal{L}^Z_{\text{int}} = -e(s_W c_W)^{-1}\mathbf{Z}_\mu \;\; \bar{\psi}\,\gamma^\mu(\mathbf{T}_3 - s_W^2\mathbf{Q})\psi$$

$$= -e(s_W c_W)^{-1}\mathbf{Z}_\mu \;\; \bar{\psi}\,\gamma^\mu[\,{}^1\!/_2(1-\gamma^5)\mathbf{T}_3 - s_W^2\mathbf{Q}\,]\,\psi$$

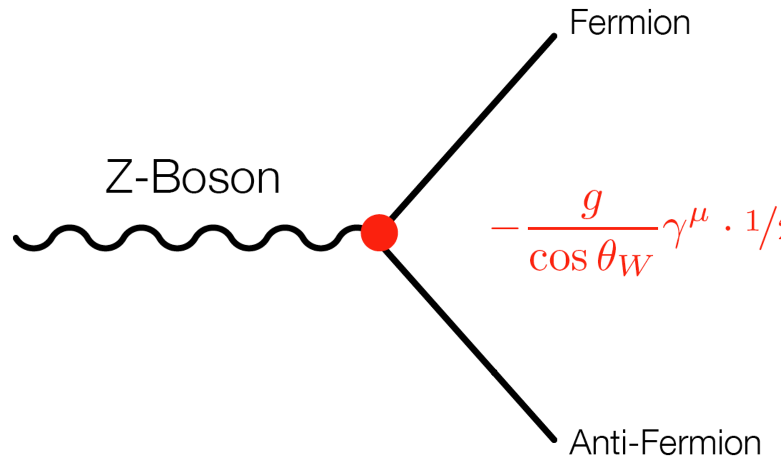
$$= -{}^g\!/_{c_W}\cdot\mathbf{Z}_\mu\cdot{}^1\!/_2\cdot(\;\bar{\psi}\,\gamma^\mu[\,\mathbf{T}_3 - 2s_W^2\mathbf{Q}\,]\psi - \;\bar{\psi}\,\gamma^\mu\gamma^5\,\mathbf{T}_3\,\psi)$$

propagator — vector coupling — axial coupling

$$\boxed{\mathcal{L}^Z_{\text{int}} = -{}^g\!/_{c_W}\cdot\mathbf{Z}_\mu\cdot{}^1\!/_2\cdot(\;\bar{\psi}\,\gamma^\mu g_V\,\psi - \;\bar{\psi}\,\gamma^\mu\gamma^5 g_A\,\psi)}$$

Z-boson interaction

Couplings
to the Z-Boson:



$$-\frac{g}{\cos\theta_W}\gamma^\mu \cdot 1/2 \cdot (g_V^f - g_A^f\gamma^5)$$

$g_V = T_3 - 2Q\sin^2\theta_W$
$g_A = T_3$

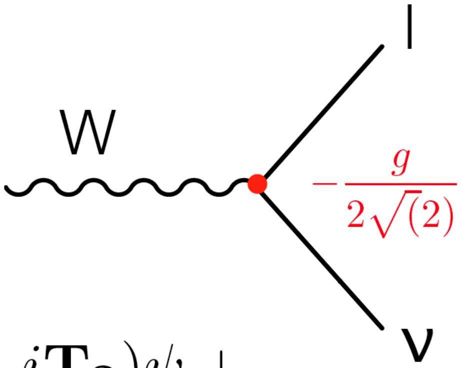
Standard Model	g_V	g_A
ν	$\frac{1}{2}$	$\frac{1}{2}$
ℓ^-	$-\frac{1}{2} + 2\sin^2\theta_W$	$-\frac{1}{2}$
$u - quark$	$+\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$	$\frac{1}{2}$
$d - quark$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}$

Couplings to
left/right handed fermions:

$g_L = ½(g_V+g_A)$
$g_R = ½(g_V-g_A)$

W-boson interaction

$$\text{"}\ell\nu W\text{"}, \text{"}udW\text{"} : e(\sqrt{2}s_W)^{-1}$$



CC interaction:
[e,ν only]

$$\mathcal{L}_{\text{int}}^{W} = -e(\sqrt{2}s_W)^{-1}\left[\mathbf{W}_\mu^+\ \bar{\psi}\gamma^\mu(\mathbf{T_1}+i\mathbf{T_2})\psi + \right.$$
$$\left. + \mathbf{W}_\mu^-\ \bar{\psi}\gamma^\mu(\mathbf{T_1}-i\mathbf{T_2})\psi\right]$$

$$= -{}^{e}/\sqrt{2}s_W\left[\mathbf{W}_\mu^+\ (\bar{\nu}_e)_L\gamma^\mu e_L + \mathbf{W}_\mu^-\ \bar{e}_L\gamma^\mu(\nu_e)_L\right]$$

propagator

left-handed

$$\mathcal{L}_{\text{int}}^{W} = -{}^{g}/\sqrt{2}\left[\mathbf{W}_\mu^+\ (\bar{\nu}_e)_L\gamma^\mu e_L + \mathbf{W}_\mu^-\ \bar{e}_L\gamma^\mu(\nu_e)_L\right]$$

Fermions with
T ≠ 0 only

Gauge Boson Self-Couplings

$$\mathcal{L}_0 \quad = \quad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu\partial_\mu\psi$$

$$F_{\mu\nu}F^{\mu\nu} \quad = \quad W_{\mu\nu}W^{\mu\nu} + B_{\mu\nu}B^{\mu\nu}$$

[electroweak only]

Transition to
covariant derivative ...

$$\partial_\mu \rightarrow \mathbf{D}_\mu$$

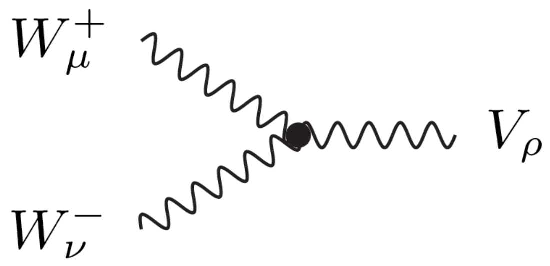
with $\mathbf{D}_\mu = \partial_\mu + ig\mathbf{W}^a_\mu\mathbf{T}^a + ig'\mathbf{B}_\mu\mathbf{Y}$

yields ...

1. Invariance under local gauge transformation
2. Gauge-boson self-couplings ...

Gauge Boson Self-Couplings

Triple gauge-boson couplings:

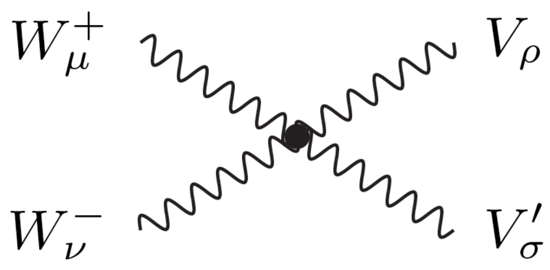


V_ρ = Z,γ:

$$\mathrm{i}eC_{WWV}\Big[g_{\mu\nu}(k_+ - k_-)_\rho + g_{\nu\rho}(k_- - k_V)_\mu + g_{\rho\mu}(k_V - k_+)_\nu\Big]$$

with $C_{WW\gamma} = 1, \quad C_{WWZ} = -\frac{c_\mathrm{W}}{s_\mathrm{W}}$

Quartic gauge-boson couplings:



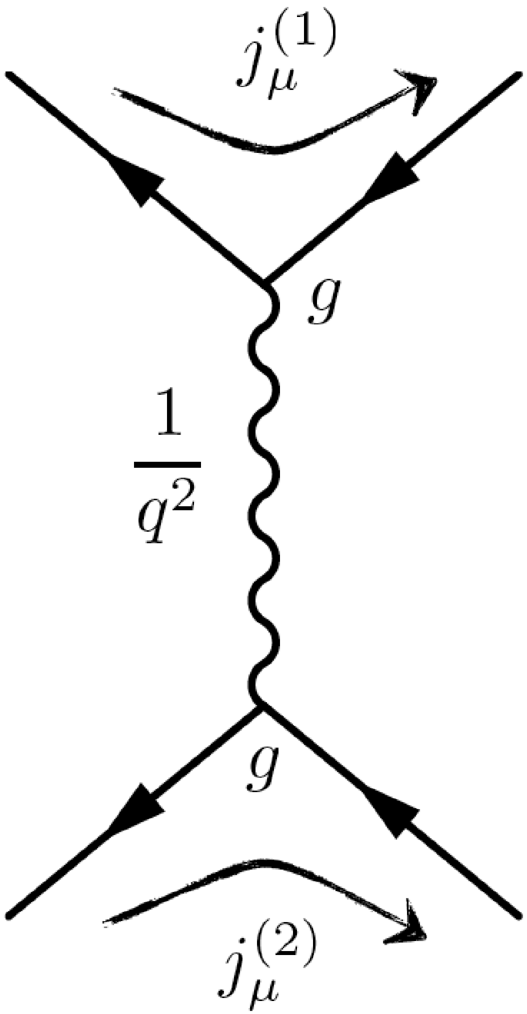
V_ρ,$V_{\rho'}$ = (W,W),(Z,Z),(Z,γ),(γ,γ):

$$\mathrm{i}e^2C_{WWVV'}\Big[2g_{\mu\nu}g_{\rho\sigma} - g_{\mu\rho}g_{\sigma\nu} - g_{\mu\sigma}g_{\nu\rho}\Big]$$

with $C_{WW\gamma\gamma} = -1, \quad C_{WW\gamma Z} = \frac{c_\mathrm{W}}{s_\mathrm{W}},$

$C_{WWZZ} = -\frac{c_\mathrm{W}^2}{s_\mathrm{W}^2}, \quad C_{WWWW} = \frac{1}{s_\mathrm{W}^2}$

Cross section: using Feynman diagrams



Fermi's Golden Rule

$$W_{\text{fi}} = 2\pi \, |M_{\text{fi}}|^2 \cdot \frac{dN}{dE_{\text{f}}}$$

Transition probability

Matrix element

Phase space

4-vector current

$$M_{\text{fi}} = -i \int j_\mu^{(1)} \cdot \left(\frac{1}{q^2} \right) \cdot j_\mu^{(2)} d^4x$$

Propagator

$$\sigma \sim |M_{\text{fi}}|^2$$

$$\sim g^4 \cdot \left(\frac{1}{q^4} \right)$$

From the Lagrangian to cross sections

$$\sigma \sim \langle f | \mathbf{S} | i \rangle^2$$

Inelastic
Cross Section
[for $|i\rangle \neq |f\rangle$]

$$[\mathrm{Def.:}\ |t=+\infty\rangle \equiv \mathbf{S}|t=-\infty\rangle\ ]$$

Time Evolution

From Schrödinger-Equation
[Dirac picture]

$$|t\rangle = |t_0\rangle - i\int_{t_0}^{t} \mathrm{d}t'\, \mathbf{H}'(t')|t'\rangle$$

Lagrangian
of Interaction

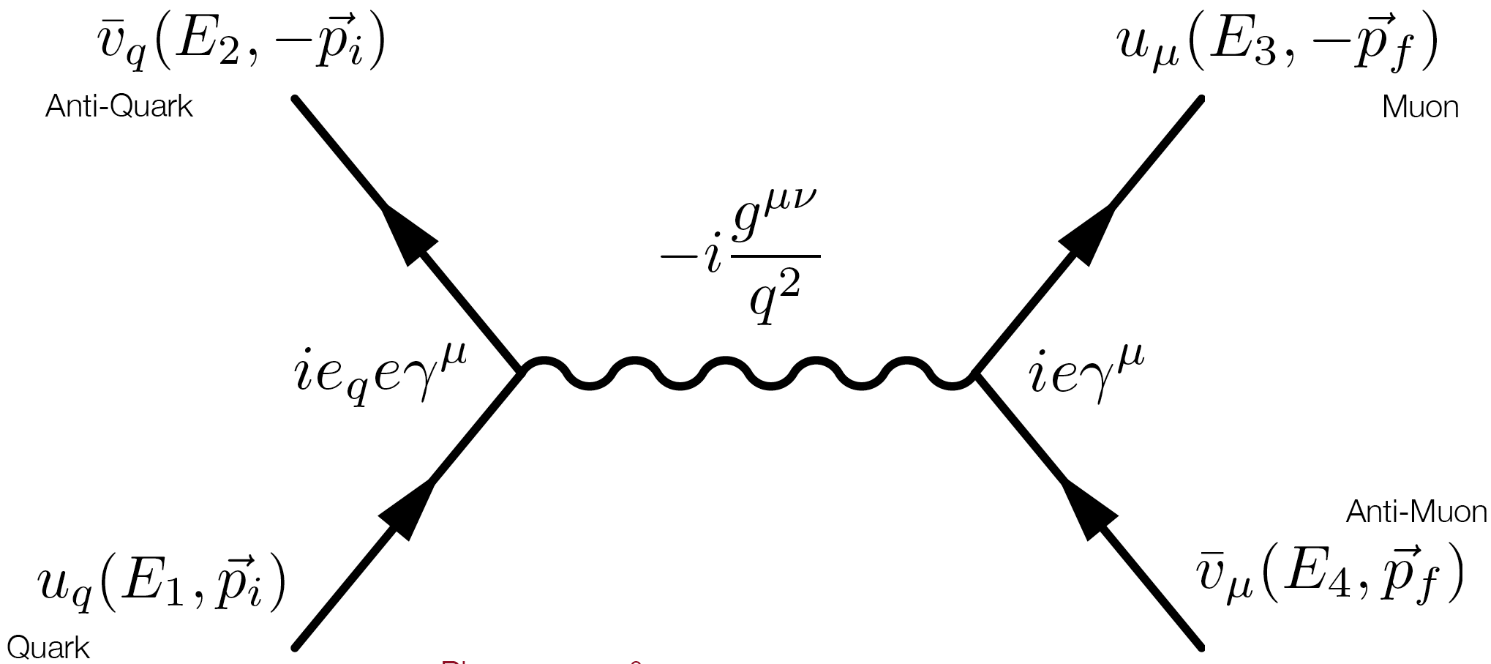
$$\mathbf{H}'(t) = -\int \mathcal{L}'(x,t)\,\mathrm{d}^3x$$

Matrix element

$$\langle f|\mathbf{S}|i\rangle \cong \delta_{fi} - i\int_{-\infty}^{\infty} \mathrm{d}t' \langle f|\mathbf{H}'(t')|i\rangle$$

➡ Feynman rules

Example: Drell-Yan Process

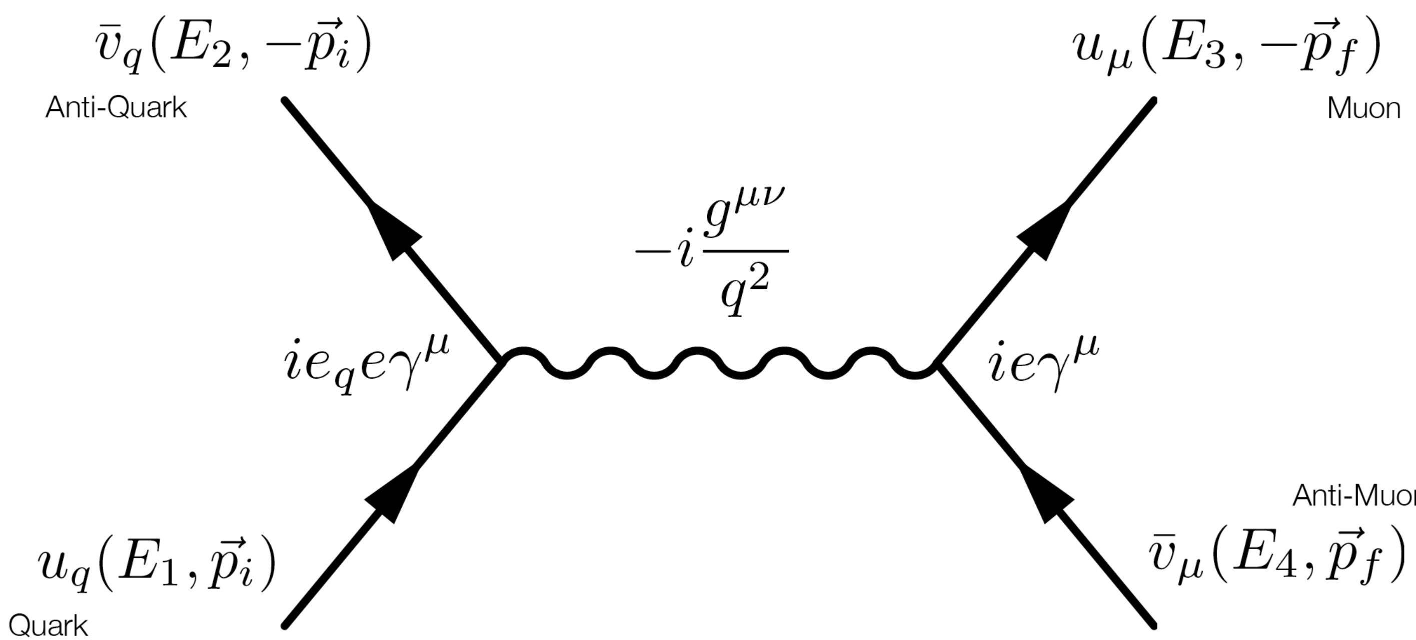


Phase space & delta functions ...

Squared Matrix element

$$\frac{d\sigma}{d\Omega} = \frac{1}{s \cdot 64\pi^2} \cdot \frac{|\vec{p}_f|}{|\vec{p}_i|} \cdot \overline{|M_{fi}|^2}$$

Example: Drell-Yan Process

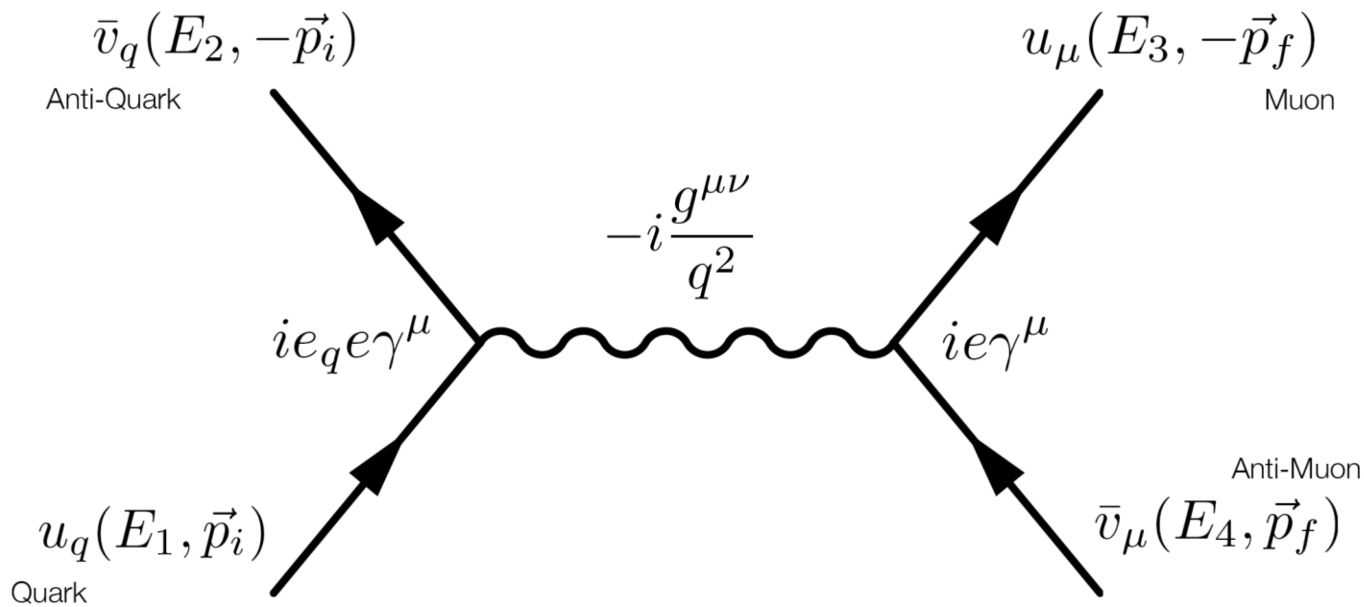


Averaging over initial spins

Summing over initial and final spins

$$|M_{fi}|^2 = \frac{1}{(2s_q+1)^2} \cdot \sum_{s_q, s'_q} \sum_{s_\mu, s'_\mu} |M_{fi}|^2$$

Example: Drell-Yan Process



Couplings · Anti-Quark · Anti-Muon

$$M_{fi} = -\frac{e_q e^2}{q^2}\bar{v}_q\gamma_\mu u_q \cdot \bar{v}_\mu\gamma^\mu u_\mu$$

Propagator · Quark · Muon

Example: Drell-Yan Process

$$\overline{|M|^2}_{q\bar{q}\to\mu\mu} = 2e_q^2 e^4 \cdot \frac{t^2+u^2}{s^2}$$

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{32\pi^2} e_q^2 \cdot \frac{1}{s} \cdot \frac{t^2+u^2}{s^2}$$

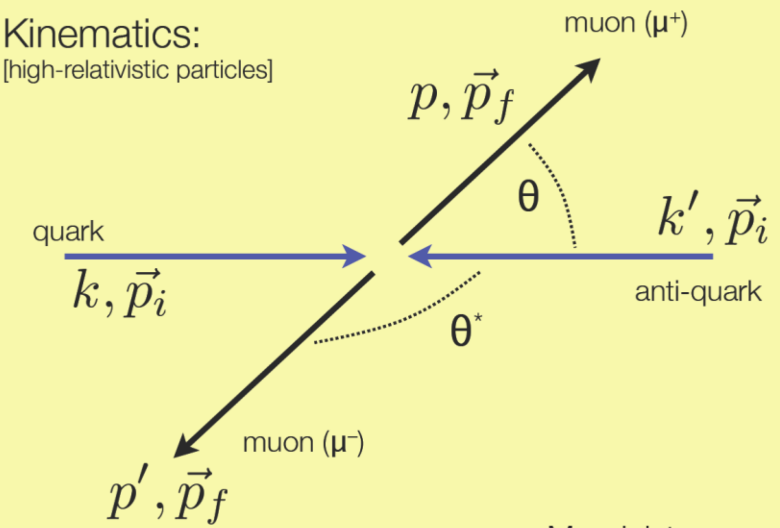
$$= \frac{e^4}{64\pi^2} e_q^2 \cdot \frac{1}{s} \cdot (1+cos^2\theta)$$

with $e^2 = 4\pi\alpha$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha}{4s} e_q^2 \cdot (1+cos^2\theta)$$

[θ in CMS frame]

Kinematics:
[high-relativistic particles]



Mandelstam variables

$$s = (k+k')^2 = 4E_i^2$$

$$t = (k-p)^2 \approx -2kp \approx -2E_i^2(1-\cos\theta^*)$$

$$\approx -\frac{s}{2}(1+\cos\theta)$$

$$u = (k-p')^2 \approx -2kp' \approx -2E_i^2(1-\cos\theta)$$

$$\approx -\frac{s}{2}(1-\cos\theta)$$