



Course on Physics at the LHC

LIP Lisbon, March - June 2014



The standard model of particle physics	Prof. João Varela (LIP, IST)	10, 13 March
Detector physics and experimental methods	Dr. Michele Gallinaro (LIP), Pedro Silva (LIP/CERN)	20, 24 March
Top quark and heavy flavor physics	Dr. João Varela (LIP), Prof. António Onofre (LIP, UM)	31 March, 7, 14 April
Statistical methods in data analysis	Dr. Pedrame Bargassa (LIP)	28 April
Standard Model Higgs boson	Dr. João Varela (LIP), Dr. André Luís Costa (LIP), Dr. Patrícia Pinto (LIP), Dr. Ricardo Gonçalves (LIP)	2, 9 May
Supersymmetry	Dr. Pedrame Bargassa (LIP)	2, 9 June
B physics and rare decays	Dr. Nuno Leonardo (LIP/CERN)	16 June
Matter at high density and temperature	Prof. João Seixas (LIP, IST), Dr. Pietro Faccioli (LIP)	23, 30 June

Lecture 2

The Standard Model of Particle Physics at LHC

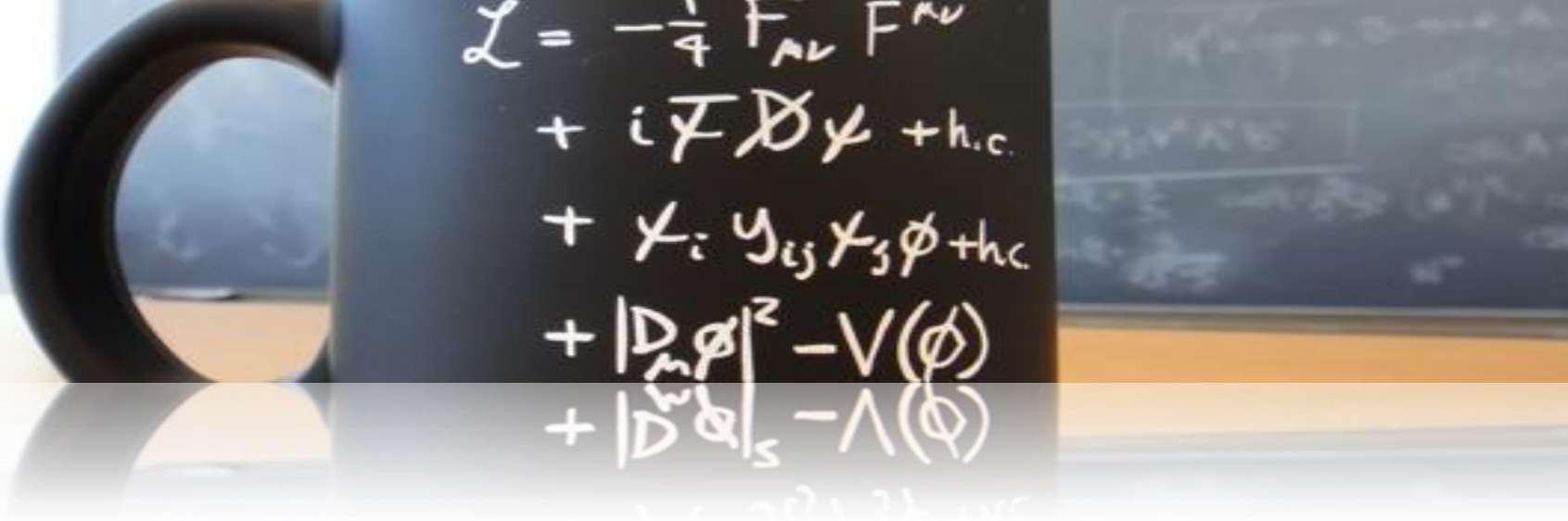
J. Varela

The lectures will take place on Mondays, between 17:00 and 18:30 at LIP, Av. Elias Garcia, 14 r/c, 1000 Lisbon - Portugal

Lecture 2 – The Standard Model at LHC

1. Electroweak theory
2. Hadron interactions
3. QCD and parton densities
4. Monte Carlo generators
5. Luminosity and cross-section measurements
6. Minum bias events
7. Jet physics

Electroweak theory


$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i Y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi) \\ & + |D_\mu \chi|^2 - \Lambda(\chi)\end{aligned}$$

Electroweak Theory

Unified theory of electromagnetic and weak interactions

Non-abelian gauge group: $SU(2)_T \times U(1)_Y$

[T: weak isospin \rightarrow coupling g , Y: hypercharge \rightarrow 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

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

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

Rich **flavor** phenomenology ...

$T = \frac{1}{2}$

$T = 0$

The SM Lagrangian

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

Free Fields (pointing to \mathcal{L}_0) Interaction (pointing to \mathcal{L}')

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

Gauge Bosons (pointing to $F_{\mu\nu}F^{\mu\nu}$) Fermions (pointing to $i\bar{\psi}\gamma^\mu\partial_\mu\psi$)

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

Fermion-Boson
Coupling (pointing to $e\bar{\psi}\gamma^\mu A_\mu\psi$)

$$eA_\mu = \frac{g_s}{2}\lambda_\nu G_\mu^\nu + \frac{g}{2}\vec{\tau} \cdot \vec{W}_\mu + \frac{g'}{2}Y B_\mu$$

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

Electroweak Theory

W and Z masses: connected via weak mixing angle

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

Couplings to W and Z

[here: leptons only]

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

$$\begin{aligned} \mathcal{L}^{\text{CC}} &= -\frac{g}{\sqrt{2}} \left[J_\mu^{+\text{CC}} W^{\mu,-} + J_\mu^{-\text{CC}} W^{\mu,+} \right] \\ &= -\frac{g}{\sqrt{2}} \left[\left(\bar{\nu}_e \gamma_\mu \frac{1}{2} (1 - \gamma_5) \mathbf{e} \right) W^{\mu,-} + \left(\bar{\mathbf{e}} \gamma_\mu \frac{1}{2} (1 - \gamma_5) \nu_e \right) W^{\mu,+} \right] \end{aligned}$$

Charged current: always flavor-changing

[quarks: mass eigenstates ≠ EW eigenstates → CKM matrix]

$$\begin{aligned} \mathcal{L}^{\text{NC}} &= -\frac{g}{2 \cos \theta_W} J_\mu^{\text{NC}} Z^\mu \\ &= -\frac{g}{2 \cos \theta_W} \left[\bar{\nu}_e \gamma_\mu \frac{1}{2} (1 - \gamma_5) \nu_e - \bar{\mathbf{e}} \gamma_\mu \frac{1}{2} (1 - \gamma_5) \mathbf{e} + 2 \sin^2 \theta_W (\bar{\mathbf{e}} \gamma_\mu \mathbf{e}) \right] Z^\mu \end{aligned}$$

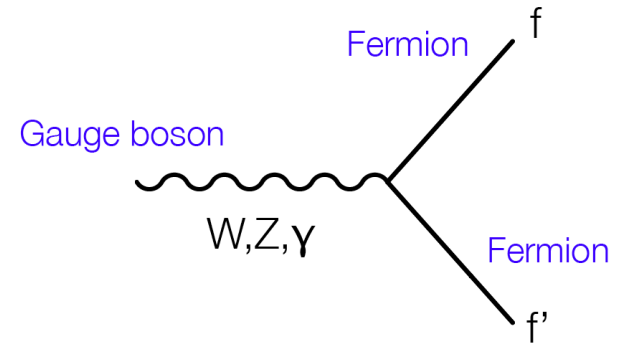
Neutral current: always flavor-conserving

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

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

with $a = 1, 2, 3$

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

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

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

Weinberg angle θ_W

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

e.m. current
neutral current
charged current

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

Fermion-Boson Interaction

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

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

charge

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

3rd isospin component

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

isospin raising operator

Coupling strengths:

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

"l ν W", "udW" : $e(\sqrt{2}s_W)^{-1}$
[left-handed only]

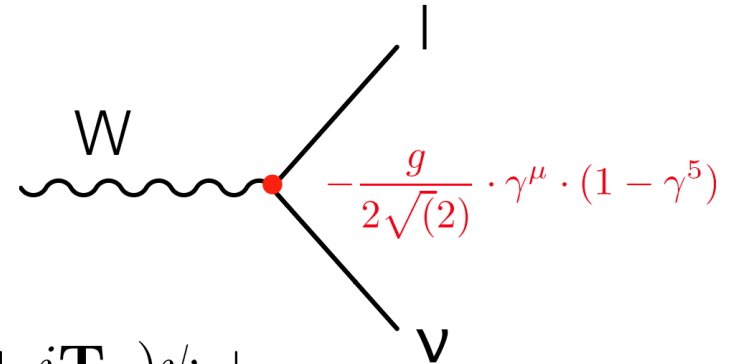
Flavor Quantum Numbers

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

- T : Weak Isospin
- T_3 : 3rd Isospin Component
- Y : Hypercharge
- Q : Charge [=T₃-Y]

W-boson interaction

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



CC interaction:

[e,ν only]

$$\mathcal{L}_{\text{int}}^W = -e(\sqrt{2}s_W)^{-1} [\mathbf{W}_\mu^+ \bar{\psi} \gamma^\mu (\mathbf{T}_1 + i\mathbf{T}_2) \psi + \mathbf{W}_\mu^- \bar{\psi} \gamma^\mu (\mathbf{T}_1 - i\mathbf{T}_2) \psi]$$

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

propagator

left-handed

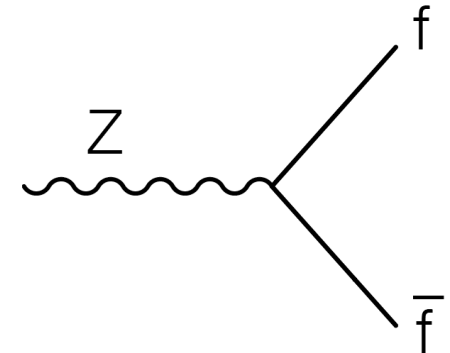
$$\mathcal{L}_{\text{int}}^W = -g/\sqrt{2} [\mathbf{W}_\mu^+ (\bar{\nu}_e)_L \gamma^\mu e_L + \mathbf{W}_\mu^- \bar{e}_L \gamma^\mu (\nu_e)_L]$$

Fermions with $T \neq 0$ only

Z-boson interaction

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

NC interaction:



$$\begin{aligned} \mathcal{L}_{\text{int}}^Z &= -e(s_W c_W)^{-1} \mathbf{Z}_\mu \bar{\psi} \gamma^\mu (\mathbf{T}_3 - s_W^2 \mathbf{Q}) \psi \\ &= -e(s_W c_W)^{-1} \mathbf{Z}_\mu \bar{\psi} \gamma^\mu [1/2(1 - \gamma^5) \mathbf{T}_3 - s_W^2 \mathbf{Q}] \psi \\ &= -g/c_W \cdot \mathbf{Z}_\mu \cdot 1/2 \cdot (\bar{\psi} \gamma^\mu [\mathbf{T}_3 - 2s_W^2 \mathbf{Q}] \psi - \bar{\psi} \gamma^\mu \gamma^5 \mathbf{T}_3 \psi) \end{aligned}$$

propagator
vector coupling
axial coupling

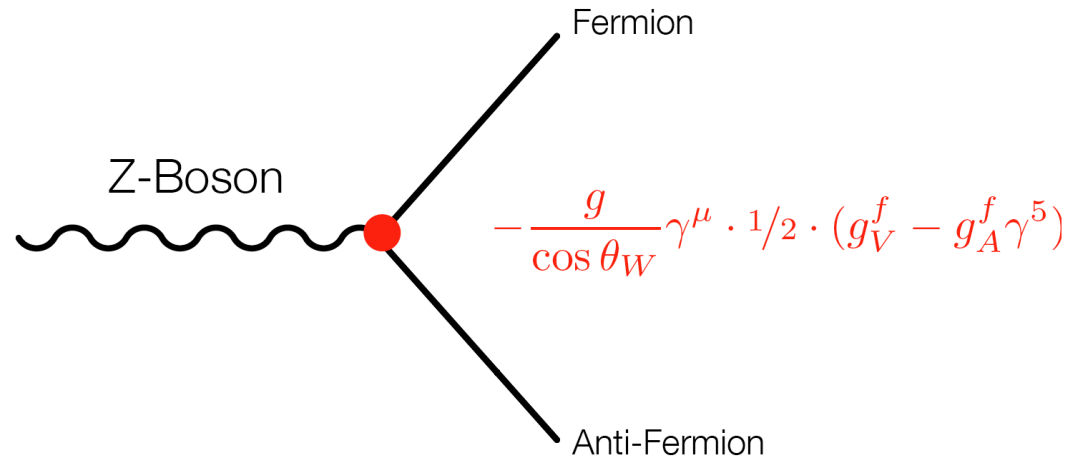
$$\mathcal{L}_{\text{int}}^Z = -g/c_W \cdot \mathbf{Z}_\mu \cdot 1/2 \cdot (\bar{\psi} \gamma^\mu g_V \psi - \bar{\psi} \gamma^\mu \gamma^5 g_A \psi)$$

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:

$$g_L = 1/2(g_V + g_A)$$

$$g_R = 1/2(g_V - g_A)$$

Gauge Boson Self-Couplings

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

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

[electroweak only]

Transition to
covariant derivative ...

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

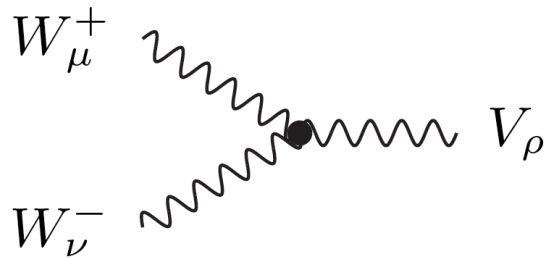
$$\text{with } \mathbf{D}_\mu = \partial_\mu + ig\mathbf{W}_\mu^a \mathbf{T}^a + ig'\mathbf{B}_\mu \mathbf{Y}$$

yields ...

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

Gauge Boson Self-Couplings

Triple gauge-boson couplings:

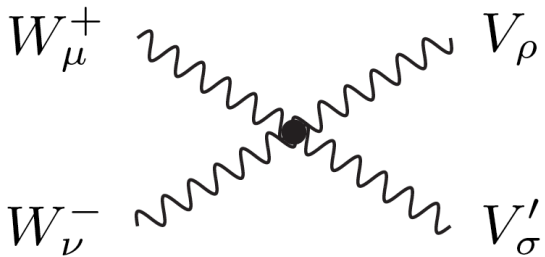


$V_\rho = Z, \gamma$:

$$ieC_{WWV} \left[g_{\mu\nu}(k_+ - k_-)_\rho + g_{\nu\rho}(k_- - k_V)_\mu + g_{\rho\mu}(k_V - k_+)_\nu \right]$$

with $C_{WW\gamma} = 1$, $C_{WWZ} = -\frac{c_W}{s_W}$

Quartic gauge-boson couplings:



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

$$ie^2 C_{WWV\rho V'} \left[2g_{\mu\nu}g_{\rho\sigma} - g_{\mu\rho}g_{\sigma\nu} - g_{\mu\sigma}g_{\nu\rho} \right]$$

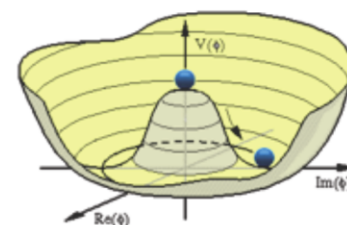
with $C_{WW\gamma\gamma} = -1$, $C_{WW\gamma Z} = \frac{c_W}{s_W}$,
 $C_{WWZZ} = -\frac{c_W^2}{s_W^2}$, $C_{WWWW} = \frac{1}{s_W^2}$

The Higgs mechanism

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

Yukawa Couplings

Higgs Field



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

Higgs Potential

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

Higgs Fermion Interaction

$$\left. \begin{array}{l} \text{Gauge Boson masses: } i\partial_{\mu} \rightarrow i(\partial_{\mu} - ieA_{\mu}) \\ \text{Fermion masses: } c_f\bar{\psi}\psi\phi \end{array} \right\} \text{and } \phi' = \phi - \rho_0$$

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_Z, m_H
3 Lepton masses	m_e, m_μ, m_τ
6 Quark masses	$m_u, m_d, m_s, m_c, m_t, m_b$.

18 free SM parameters
no neutrino masses

$$m_W^2 = \frac{1}{2} g^2 \rho_0^2$$

$$m_Z^2 = \frac{1}{2} (g^2 + g'^2) \rho_0^2$$

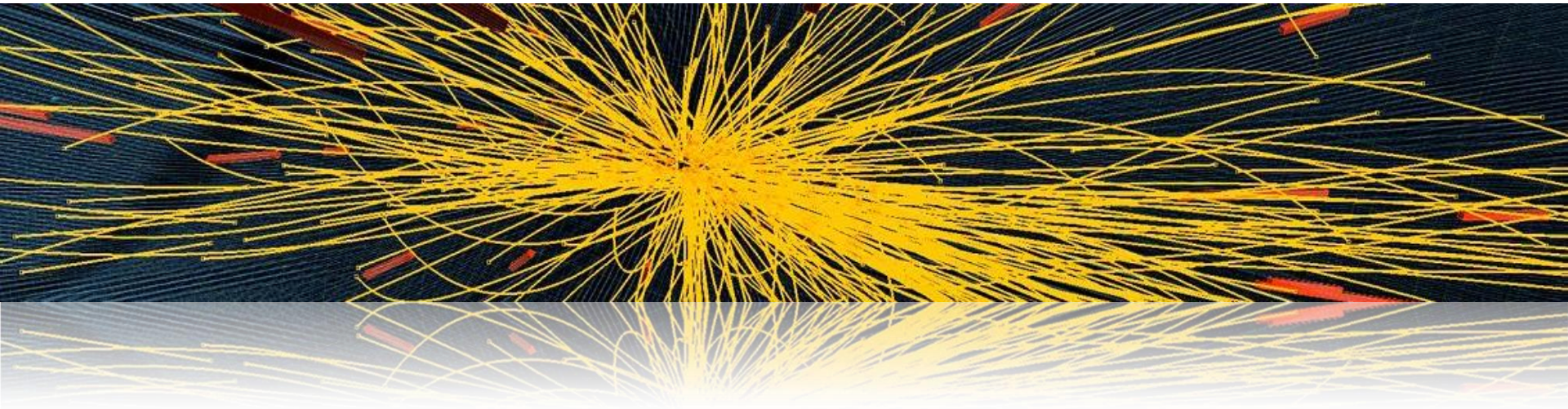
$$m_H^2 = 4 \lambda \rho_0^2$$

$$g = e / \sin \theta_W$$

$$g' = e / \cos \theta_W$$

$$m_f = c_f \rho_0$$

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

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

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

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

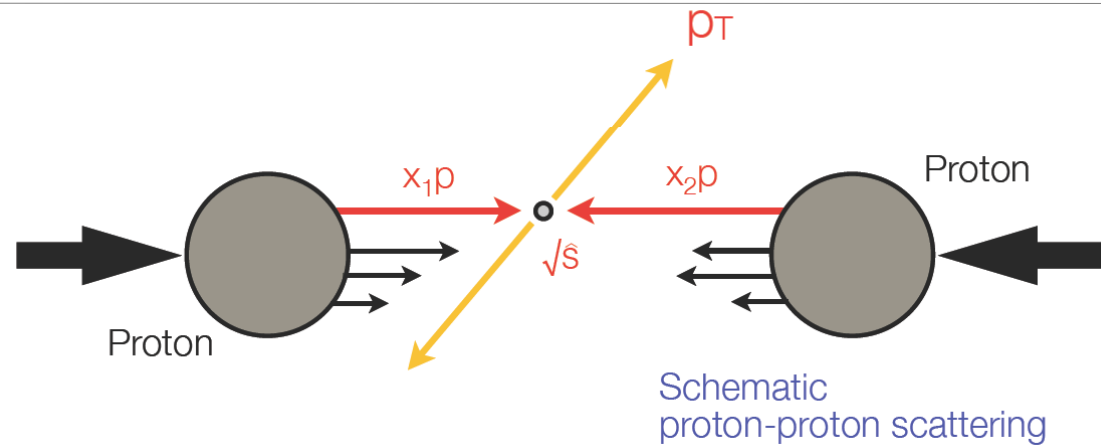
Lorentz invariance

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

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

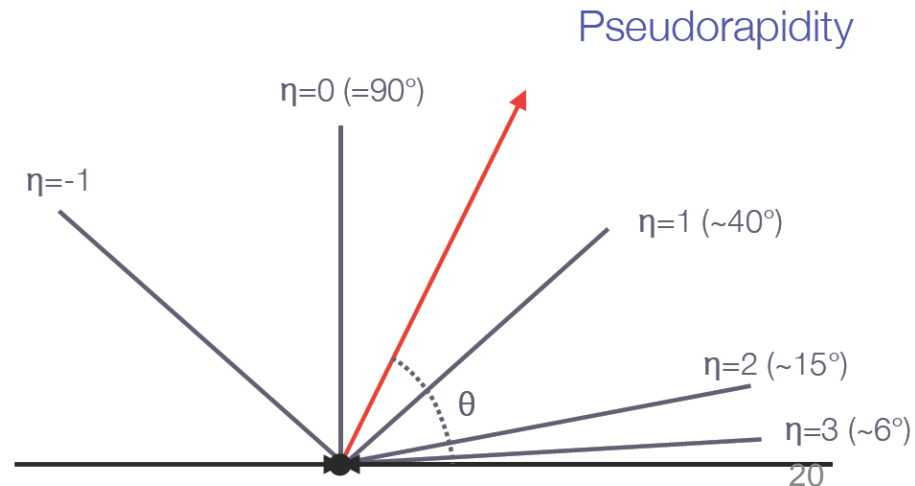
4-vector scalar product
Lorentz invariant

Kinematical variables



Relevant kinematic variables:

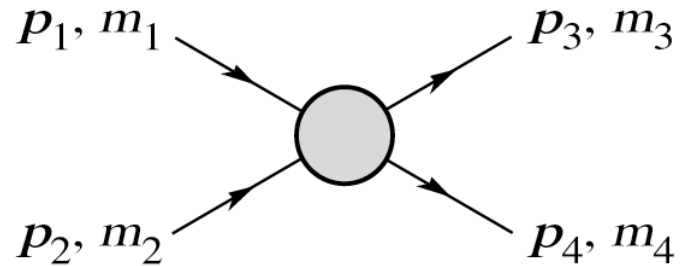
- Transverse momentum: p_T
- Rapidity: $y = \frac{1}{2} \cdot \ln \frac{E-p_z}{E+p_z}$
- Pseudorapidity: $\eta = -\ln \tan \frac{1}{2}\theta$
- Azimuthal angle: φ



Invariant mass

Invariant Mass:

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



Center of mass energy

Center-of-mass Energy:

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

Particle 2 at rest:

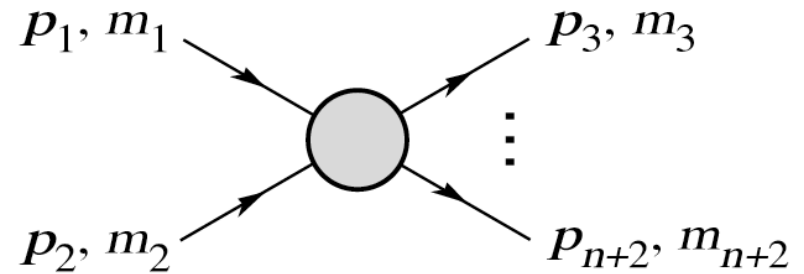
$$\sqrt{s} = E_{\text{cm}} = \left[m_1^2 + m_2^2 + 2E_1m_2 \right]^{\frac{1}{2}}$$

Particle Collider:

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

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

Cross section Matrix element Phase space



Differential
Cross Section:

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2; p_3, \dots, p_{n+2})$$

Matrix element

n-body
phase space

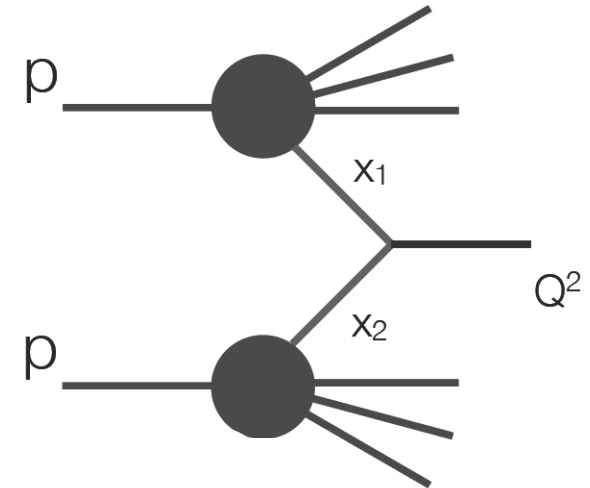
$$d\Phi_n = \dots$$

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

with $P = p_1 + p_2$

Parton distributions

Bjorken-x



Proton-proton cross section

$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(Q^2)$$

$x_{1,2}$: Bjorken-x

fractional momentum of parton
involve in hard process

Q^2 : scale; spacial resolution

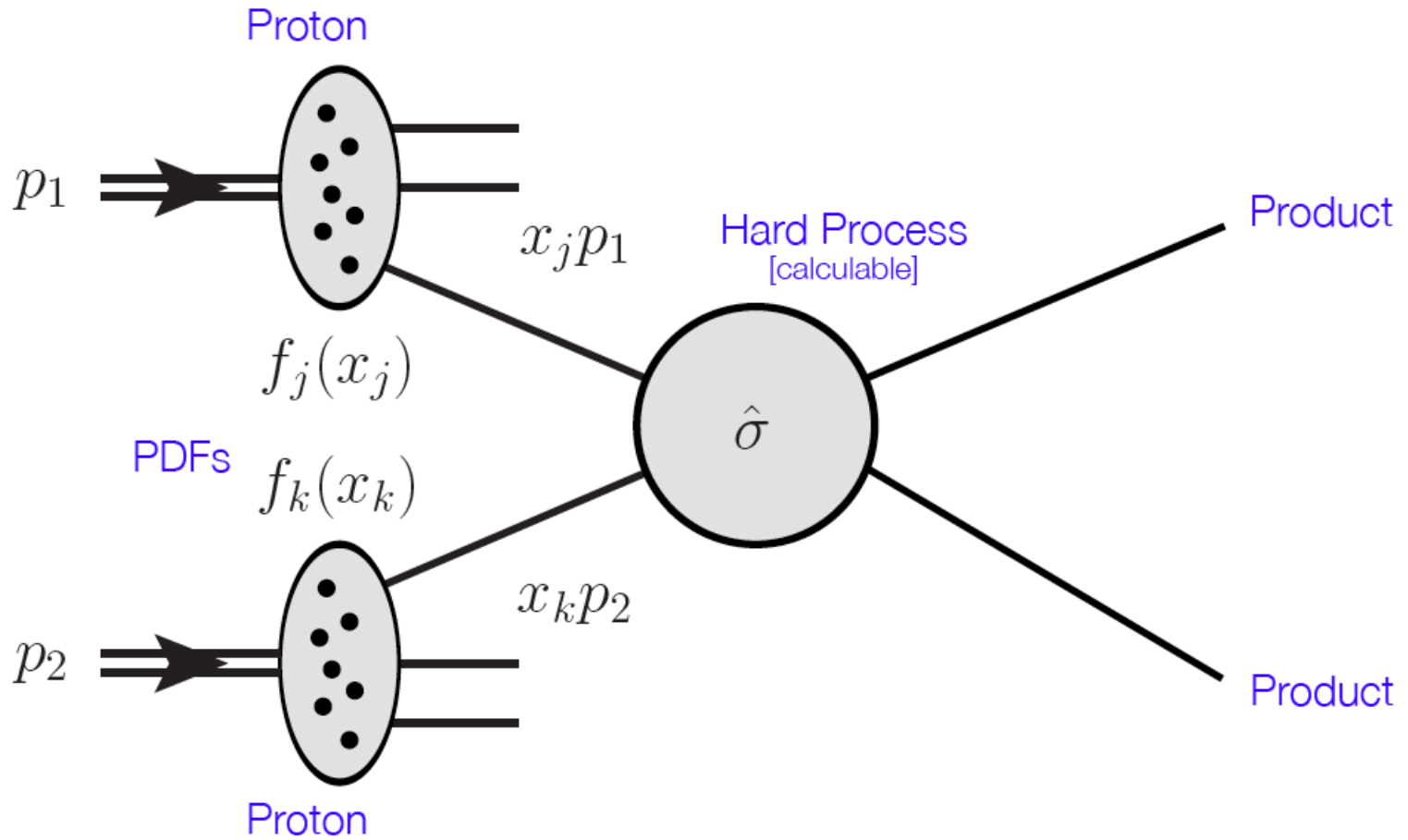
invariant parton-parton mass

f : Parton Distribution function

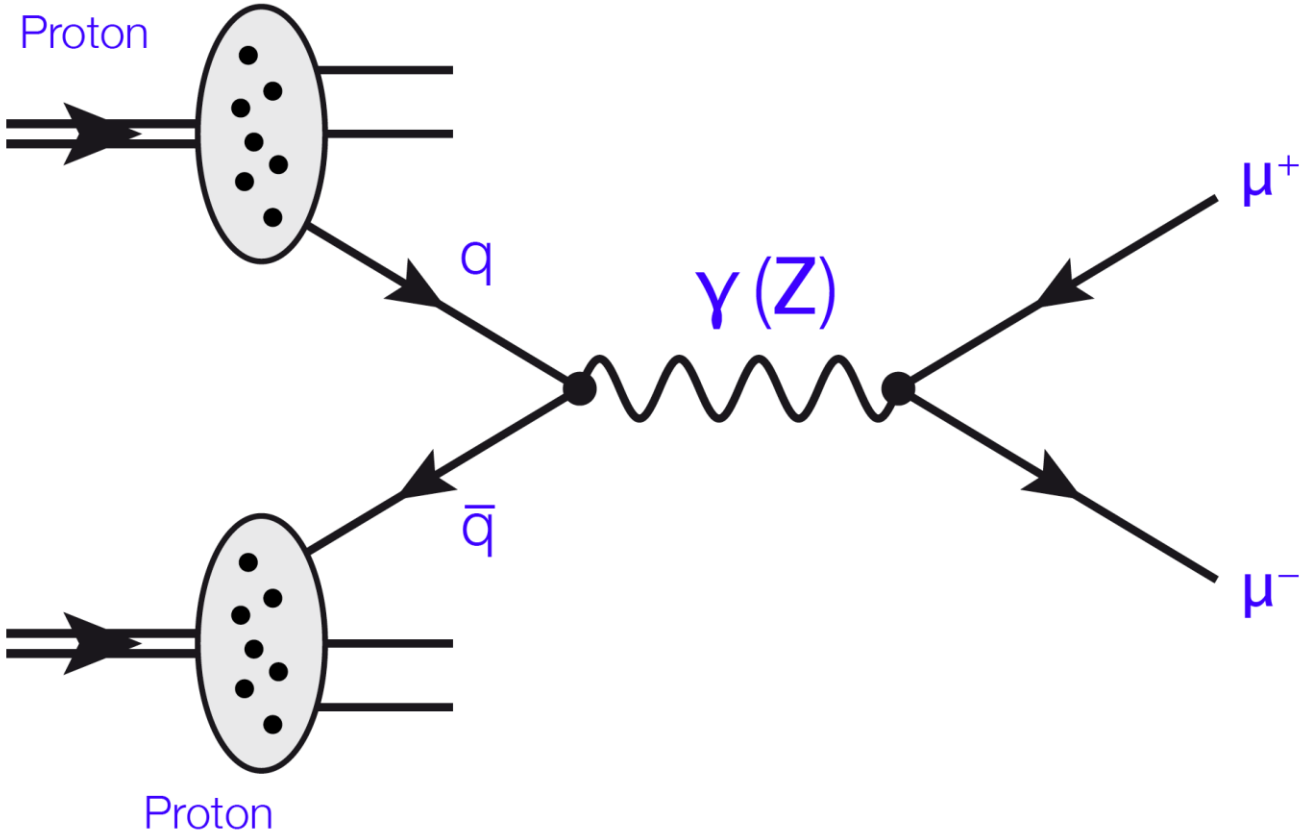
Parton content:

$$f(x, Q^2) = q(x, Q^2) \text{ or } g(x, Q^2)$$

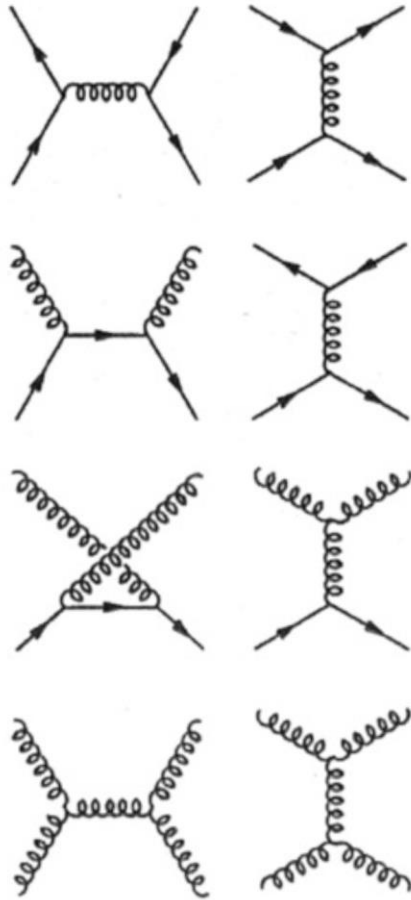
Proton-proton scattering



Example: Drell-Yan Process



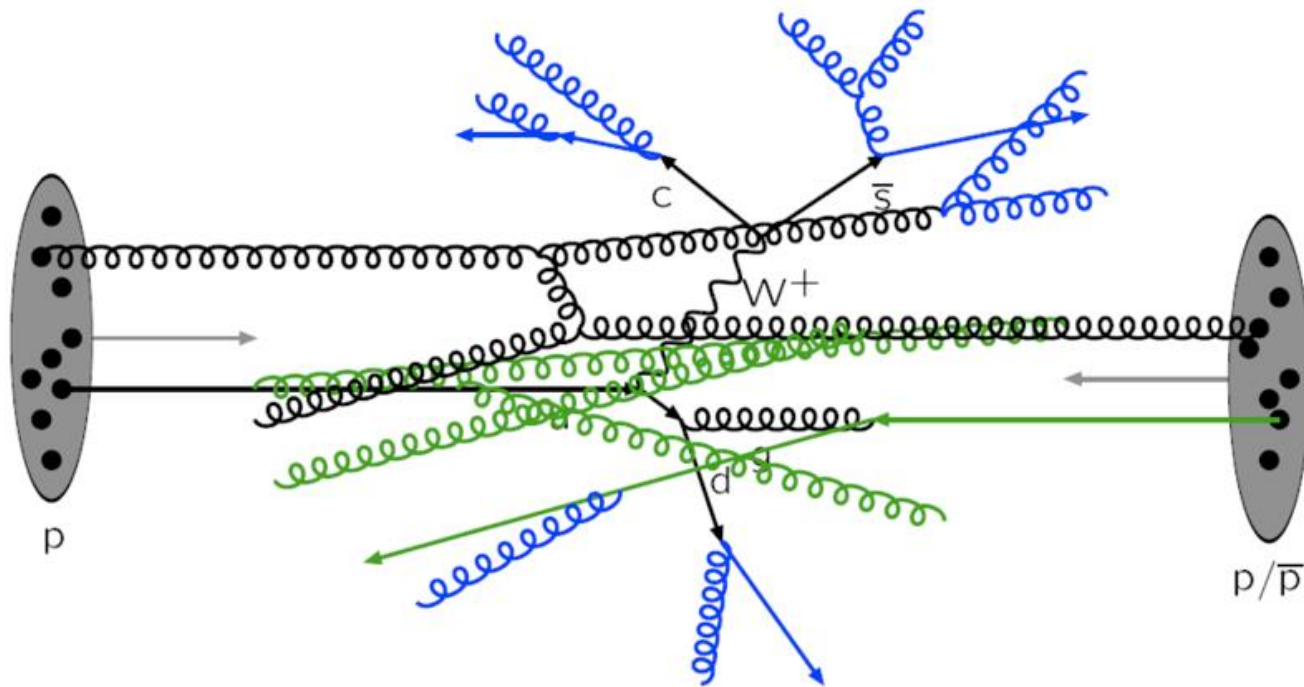
QCD Matrix Elements



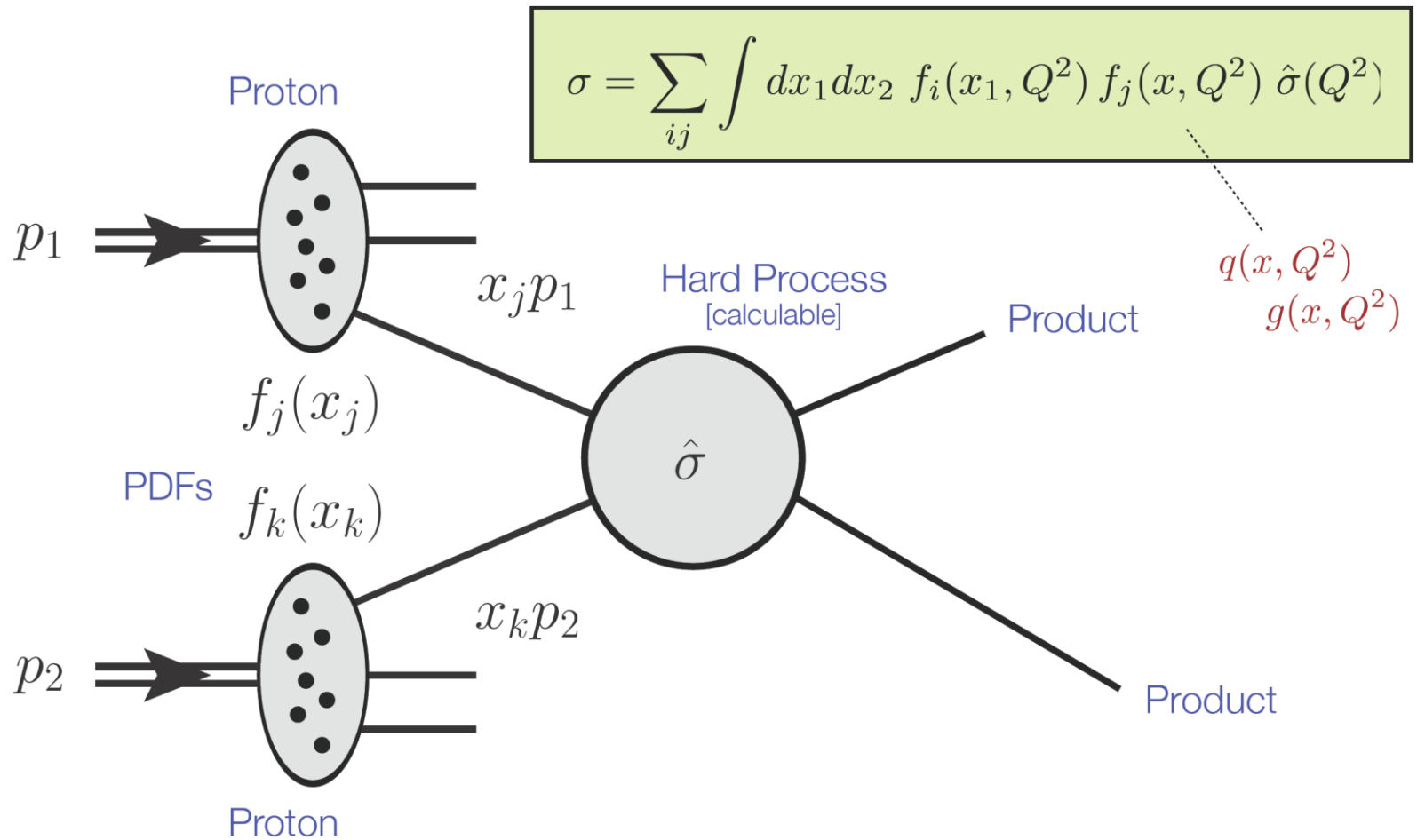
Subprocess	$ \mathcal{M} ^2/g_s^4$	$ \mathcal{M}(90^\circ) ^2/g_s^4$
$qq' \rightarrow qq'$ $q\bar{q}' \rightarrow q\bar{q}'$	$\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$	2.2
$qq \rightarrow qq$	$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2}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

Proton-Proton Scattering @ LHC

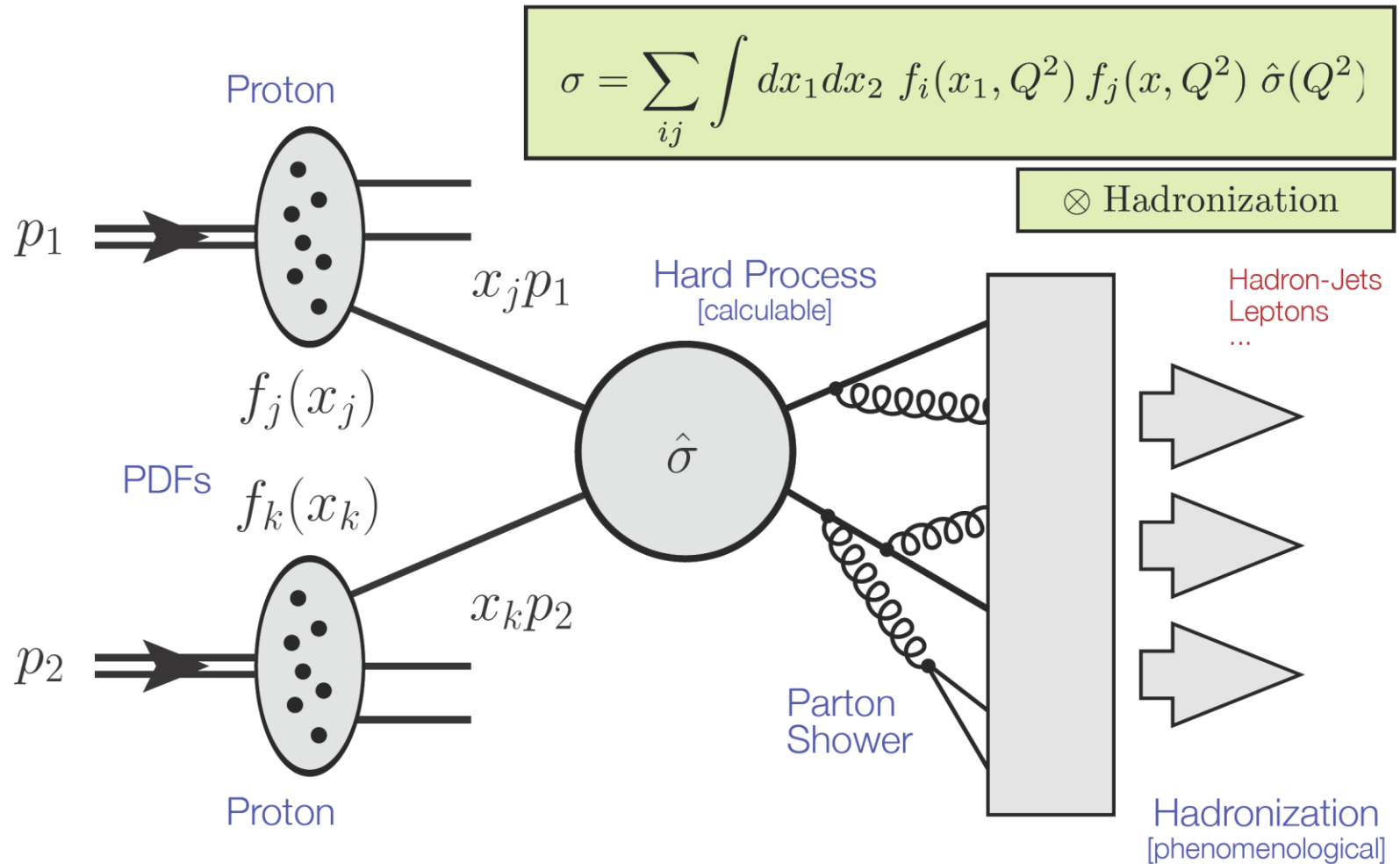
- Hard interaction: qq , gg , qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction [“underlying event”]



Proton-Proton Scattering @ LHC

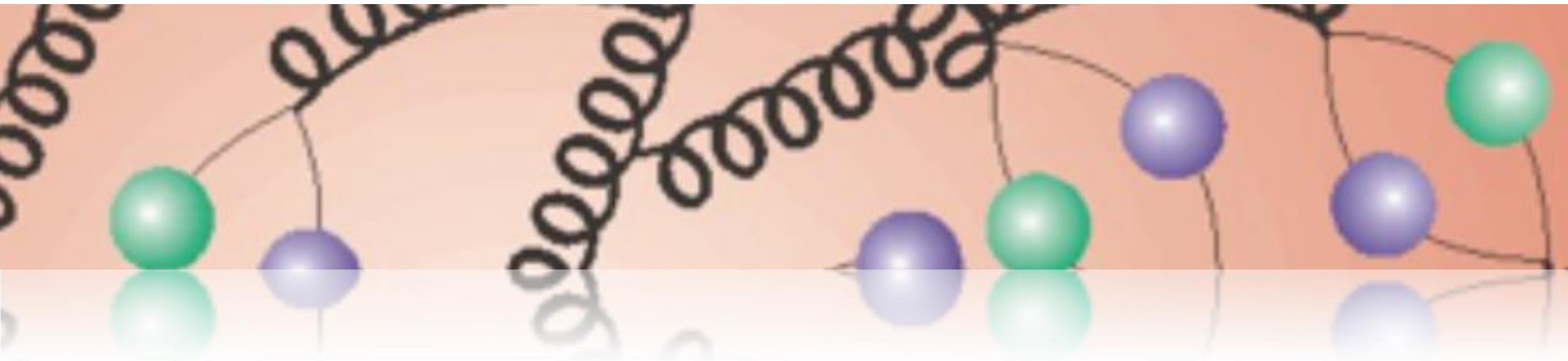


Proton-Proton Scattering @ LHC

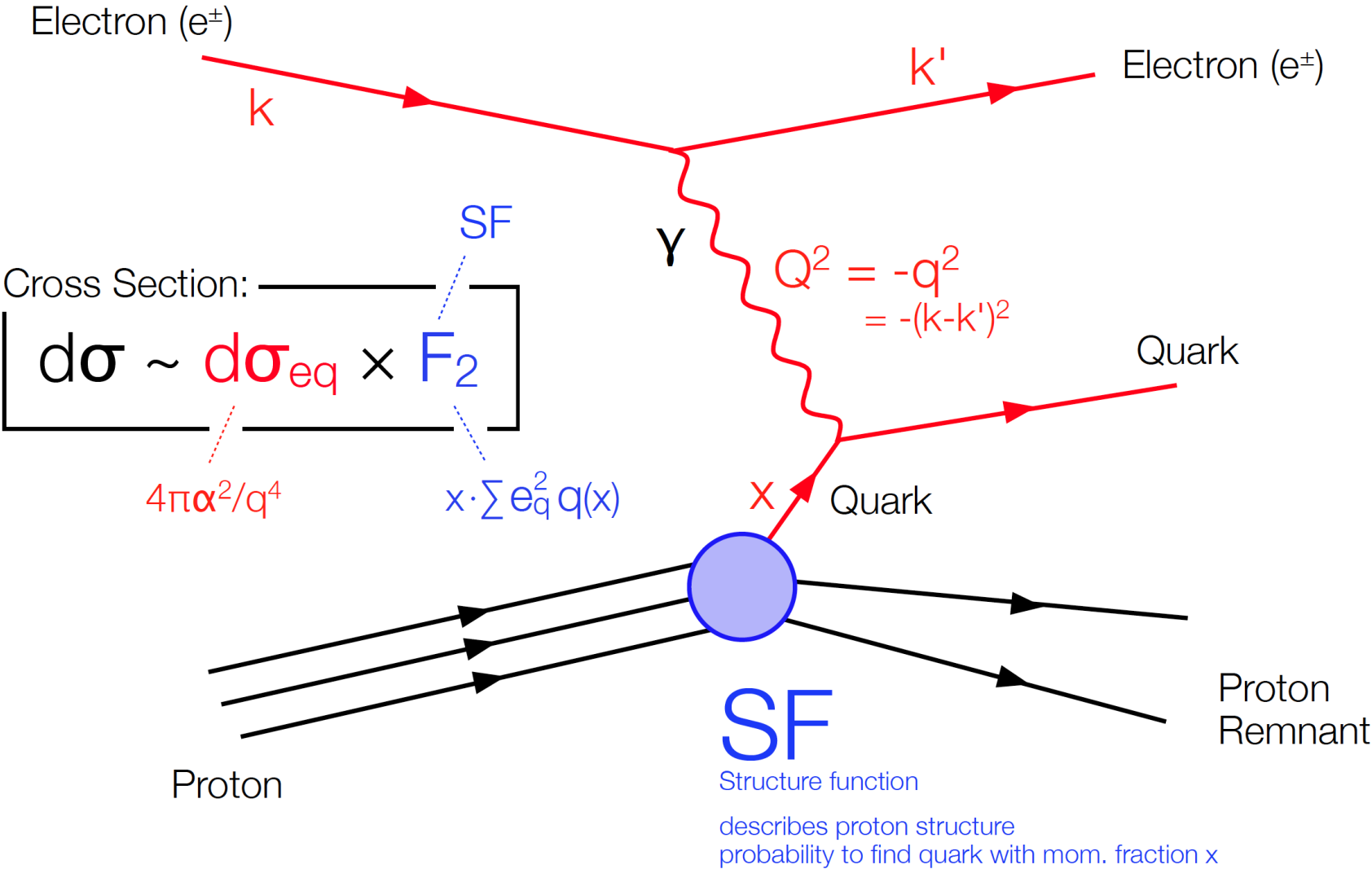


$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(Q^2)$$

QCD & parton densities

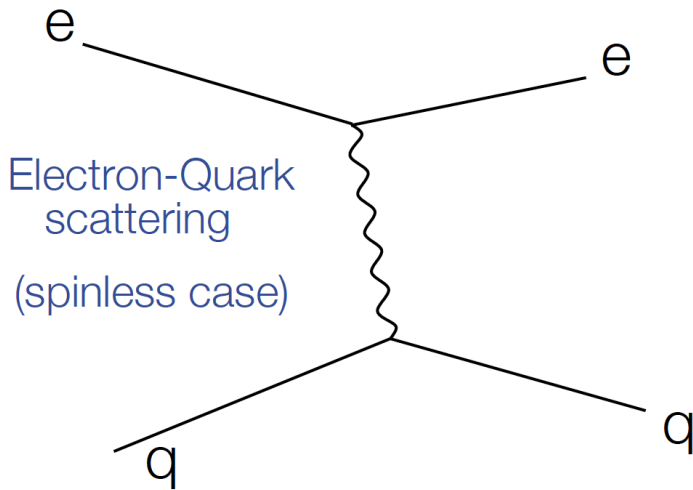


Lepton-proton scattering



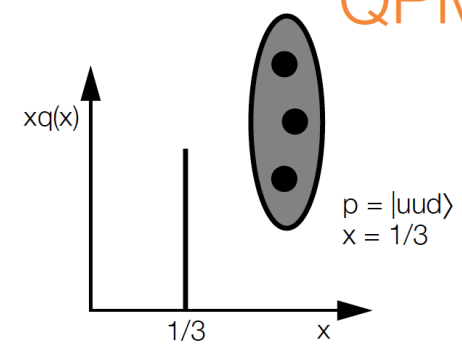
Structure Function F_2

Naive
QPM



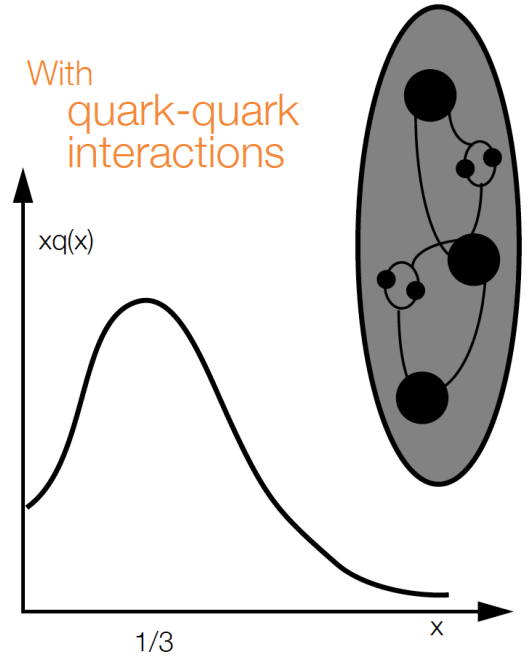
$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

Rutherford scattering on pointlike target



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

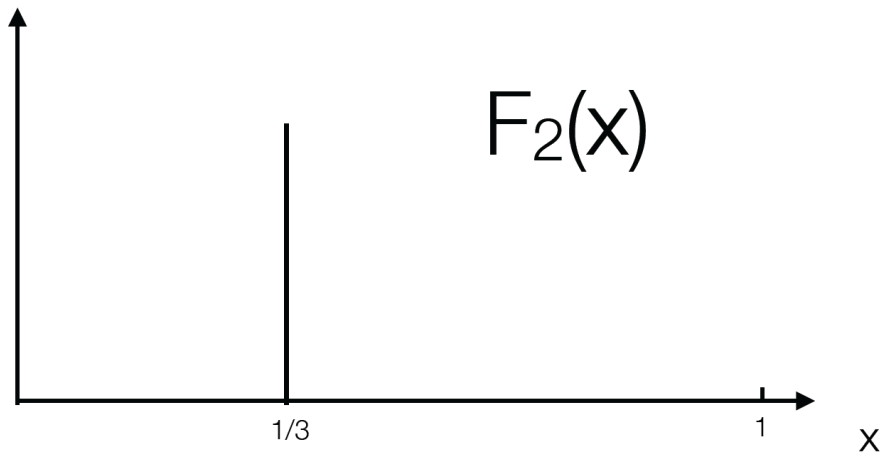
With
quark-quark
interactions



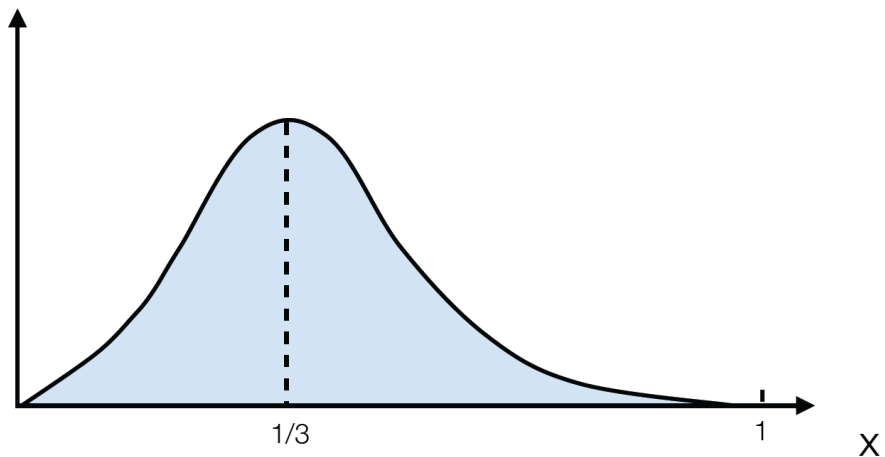
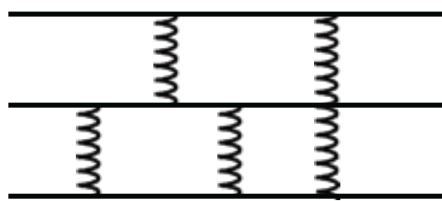
$$\begin{aligned} \frac{d\sigma(ep)}{dx dq^2} &= \frac{4\pi\alpha^2}{q^4} [e_u^2 u(x) + e_d^2 d(x) + \dots] \\ &= \frac{4\pi\alpha^2}{q^4} \frac{F_2(x)}{x} \end{aligned}$$

QPM: Structure Functions F_2 independent of Q^2

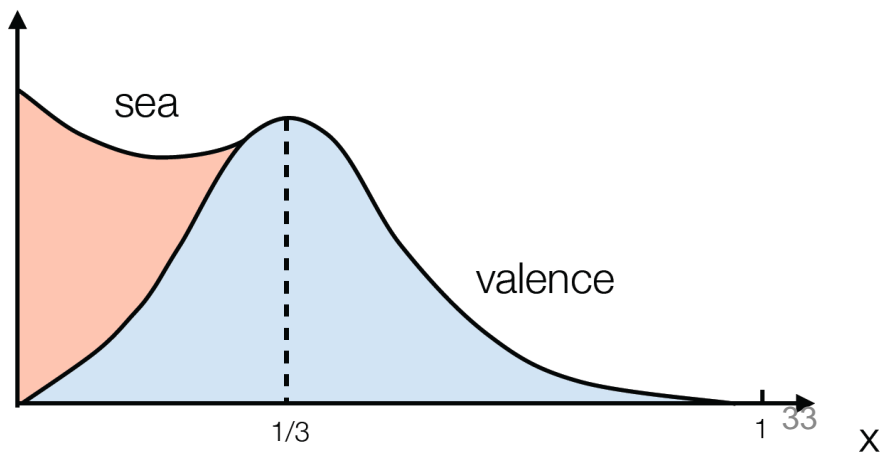
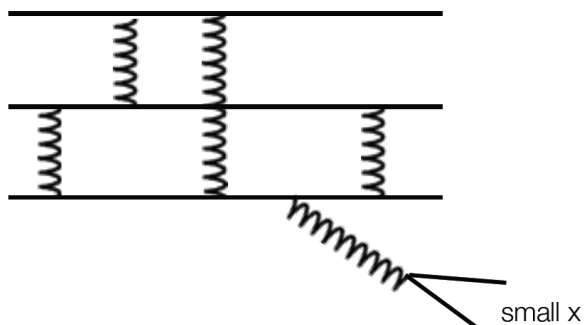
Proton Three valence quarks



Proton Three bound valence quarks



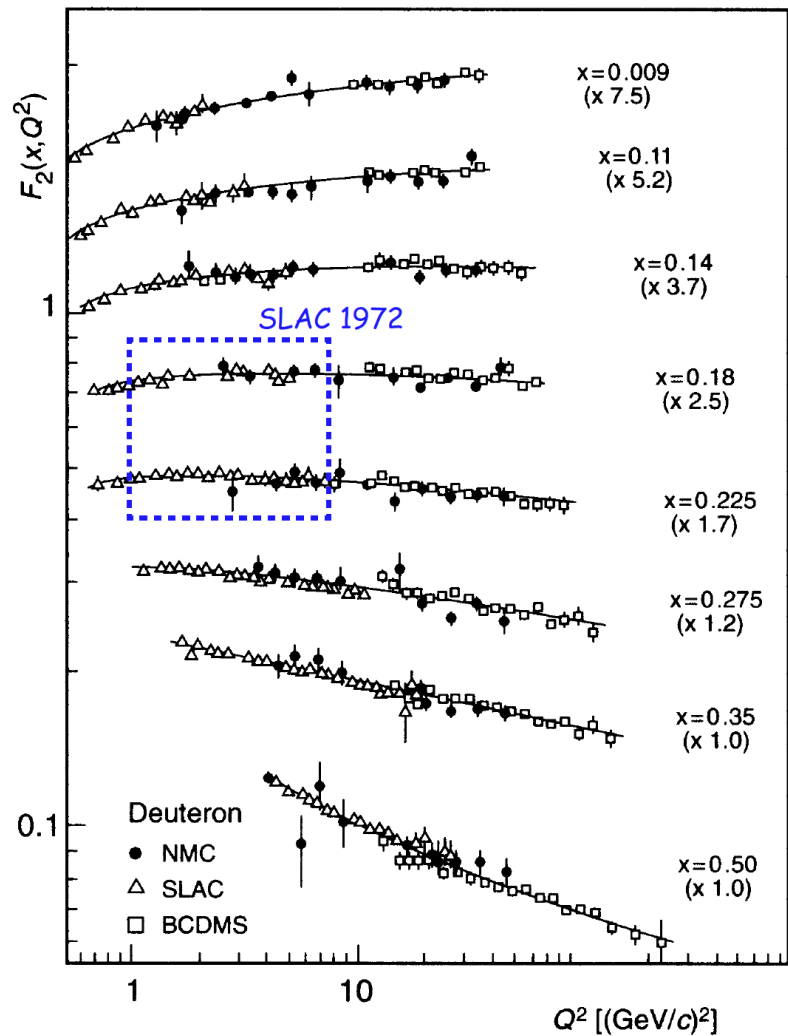
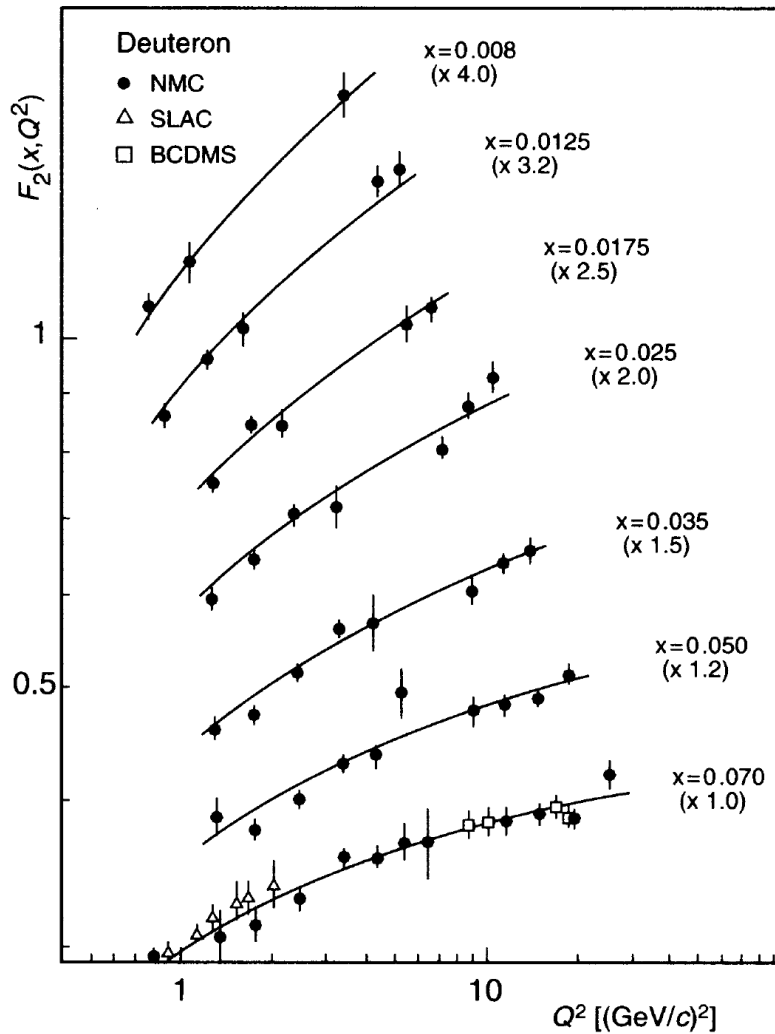
Proton Bound valence quarks + gluon radiation



[see e.g. Halzen/Martin]

Scaling violation

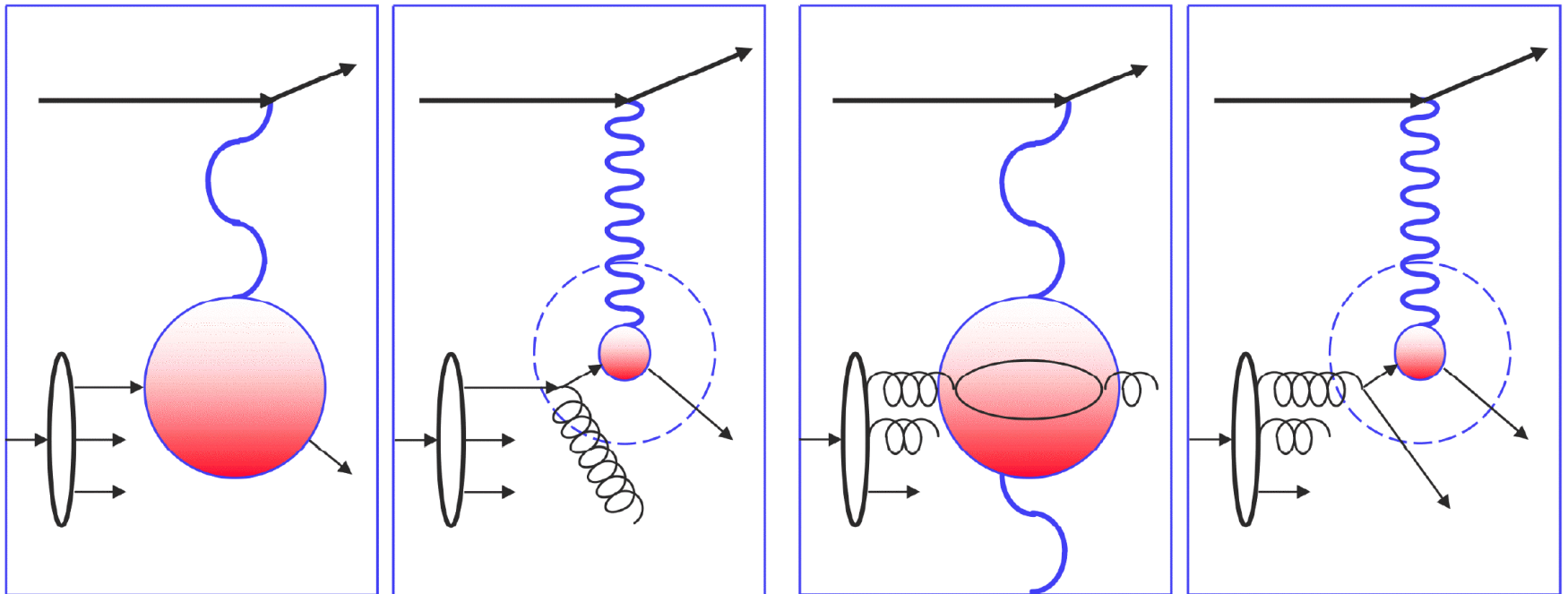
$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$



Scaling violation

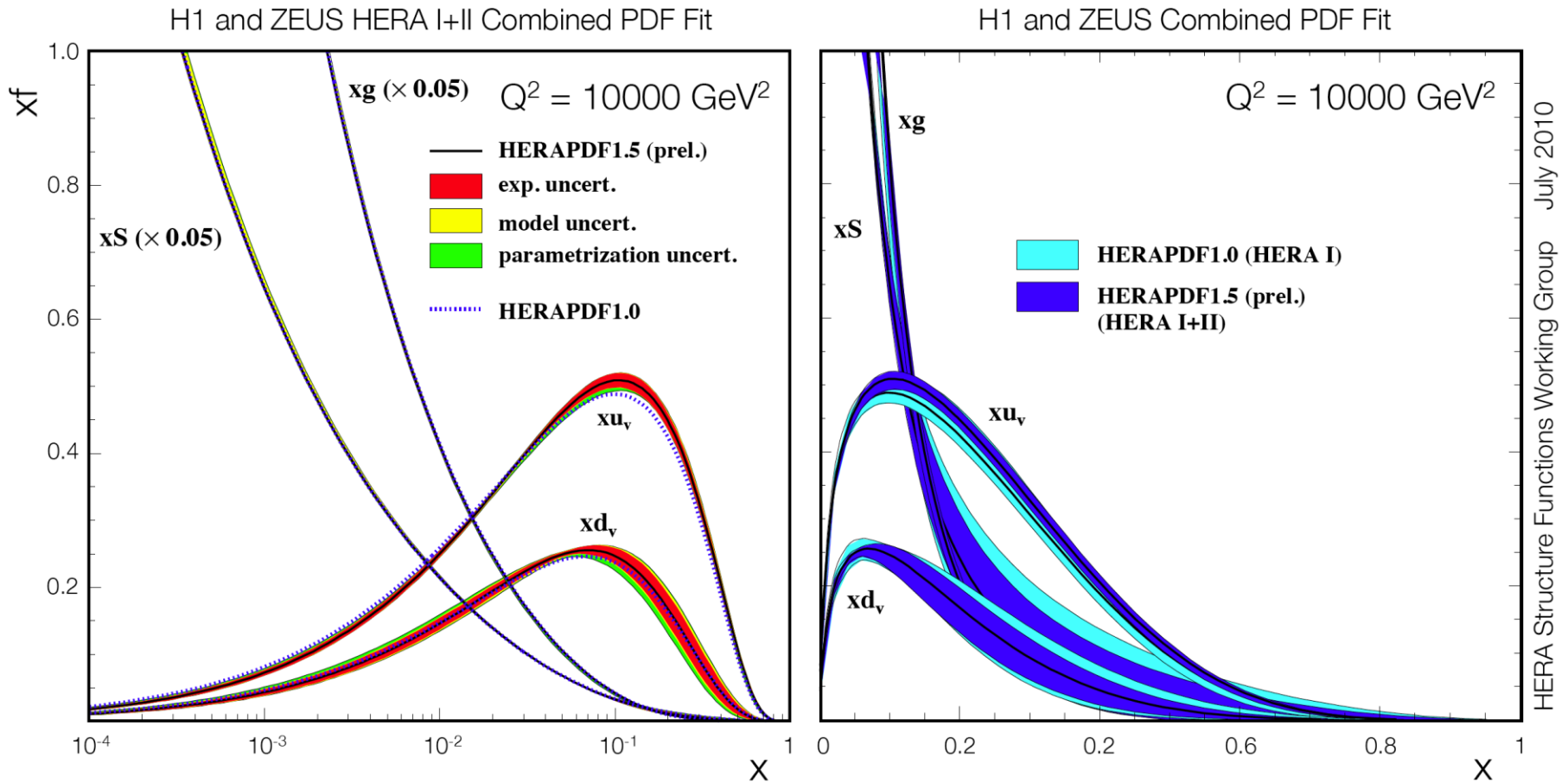
Proton quark dominated:
 $Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

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

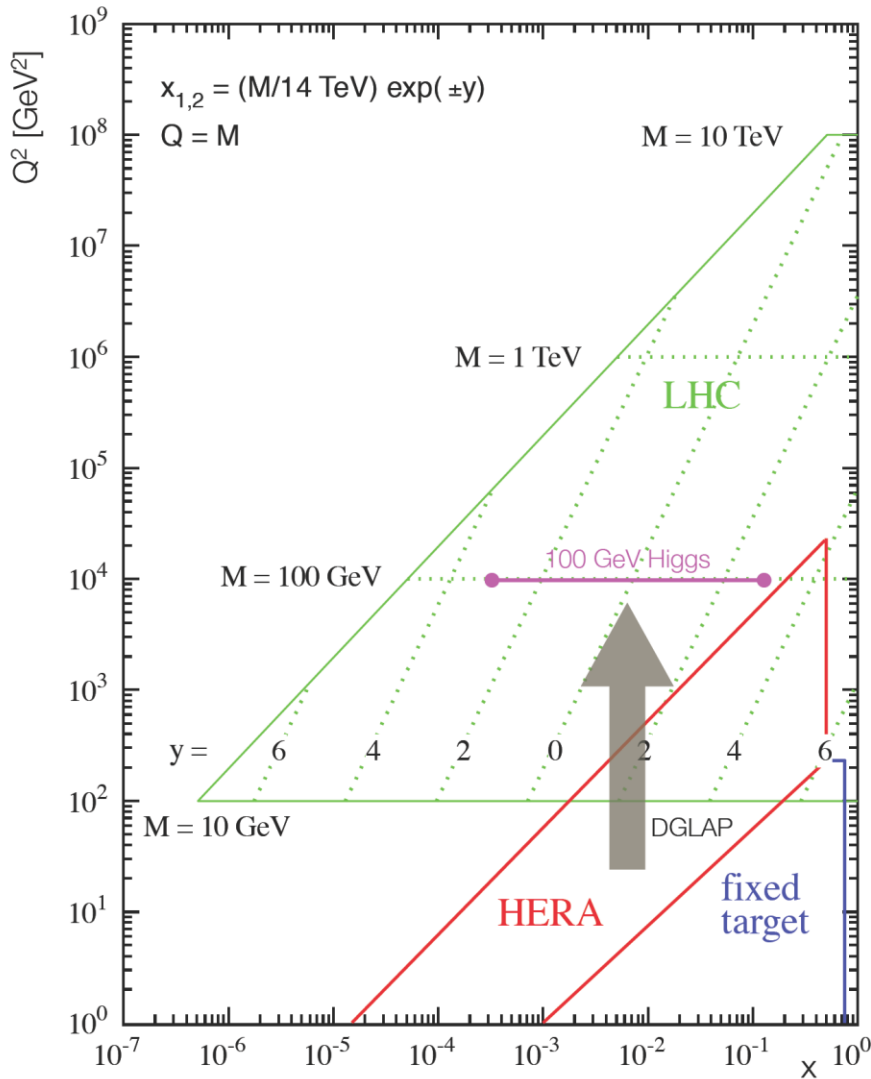
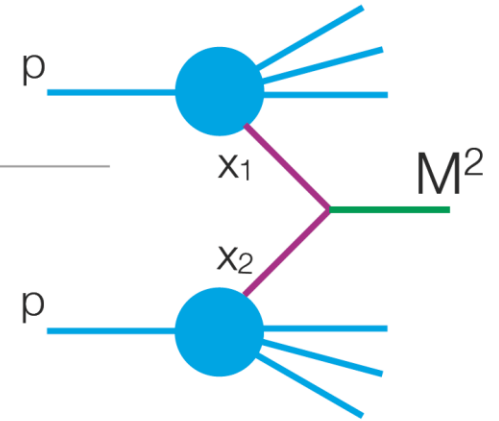


Q^2 -evolution described by DGLAP Equations

Proton parton densities



Particle production @ LHC



LHC parton kinematics

$pp \rightarrow X_M + \text{remnants}$

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 ($\sqrt{s} = 14 \text{ TeV}$)

$$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$$

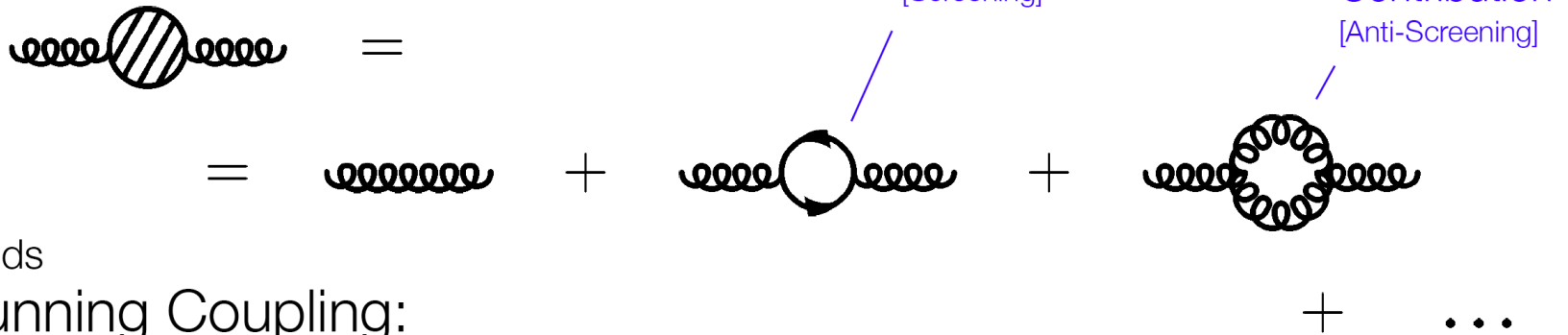
$[x_1 = x_2: \text{mid-rapidity}]$

LHC needs:

Knowledge of parton densities
Extrapolation over orders of magnitudes

Running Coupling α_s

Gluon Propagator:



Yields

Running Coupling:

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

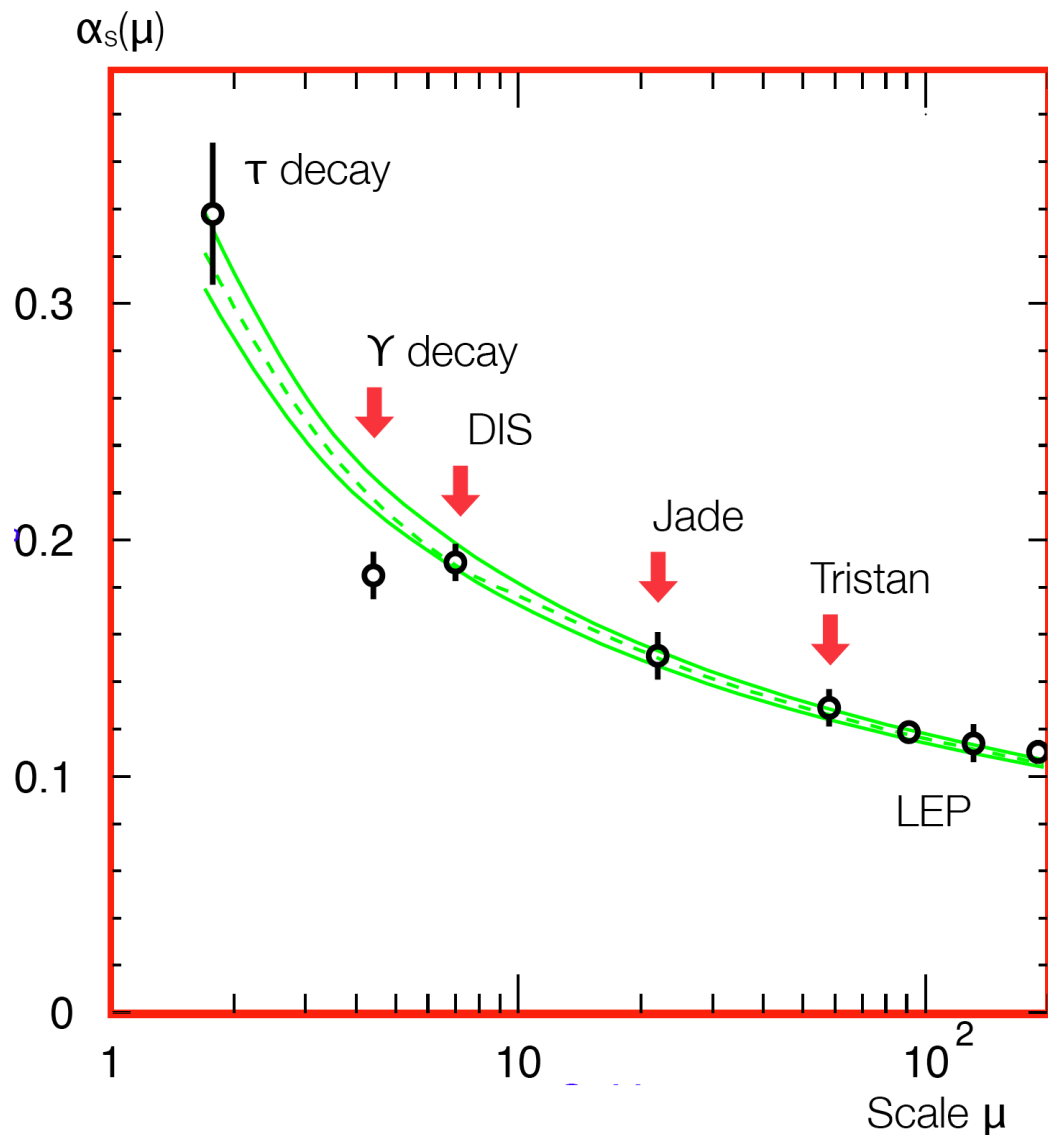
↑
Positive Sign !

QED:

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

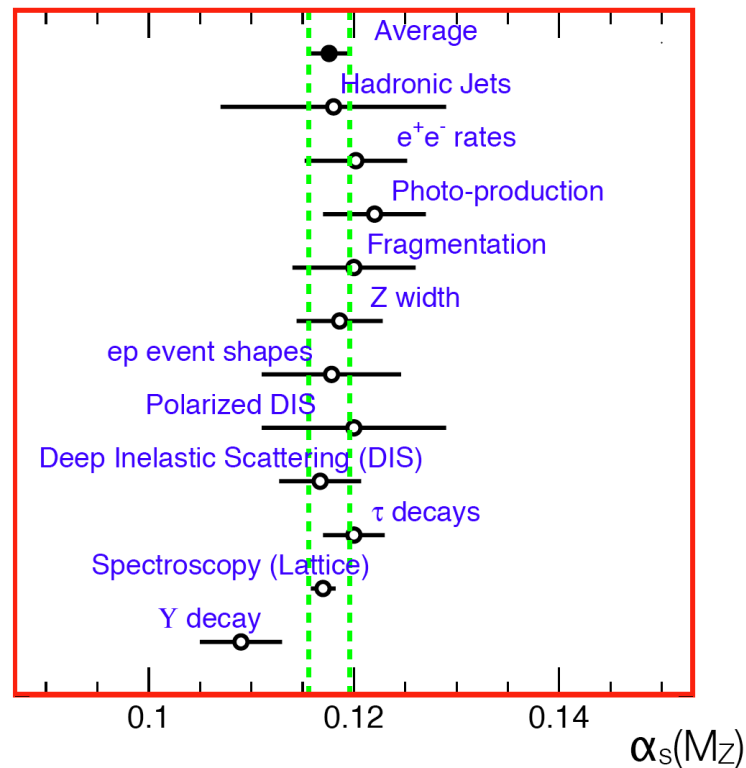
↑
Negative Sign !

Running Coupling α_s

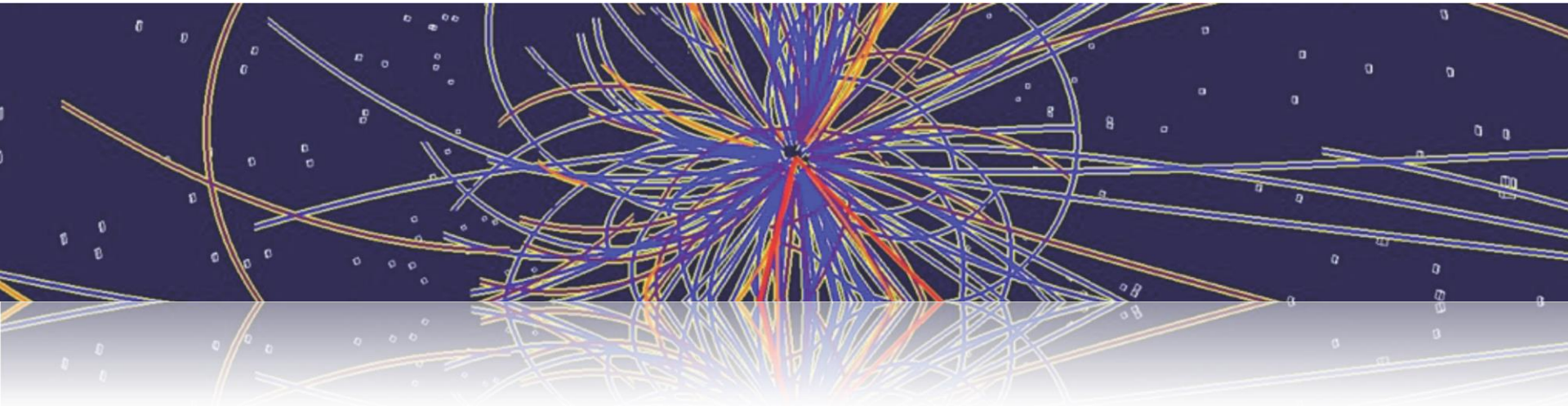


PDG '08

[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 ...

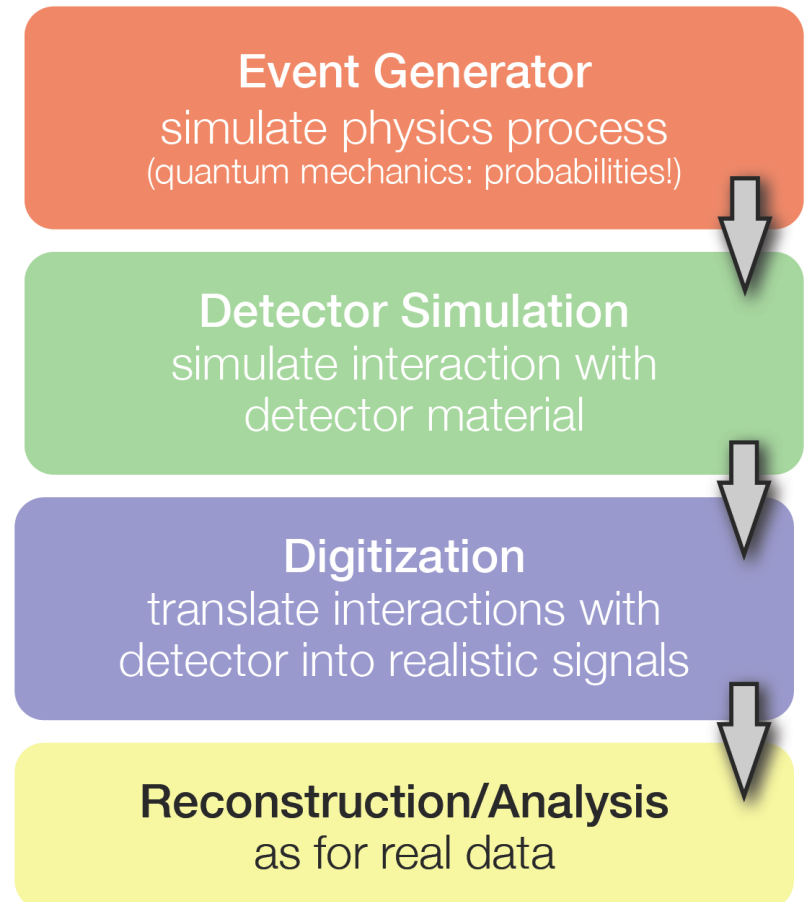
Hard partonic subprocess +
fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response
of all produced particles ...

MC simulations in particle physics



Event Generator types

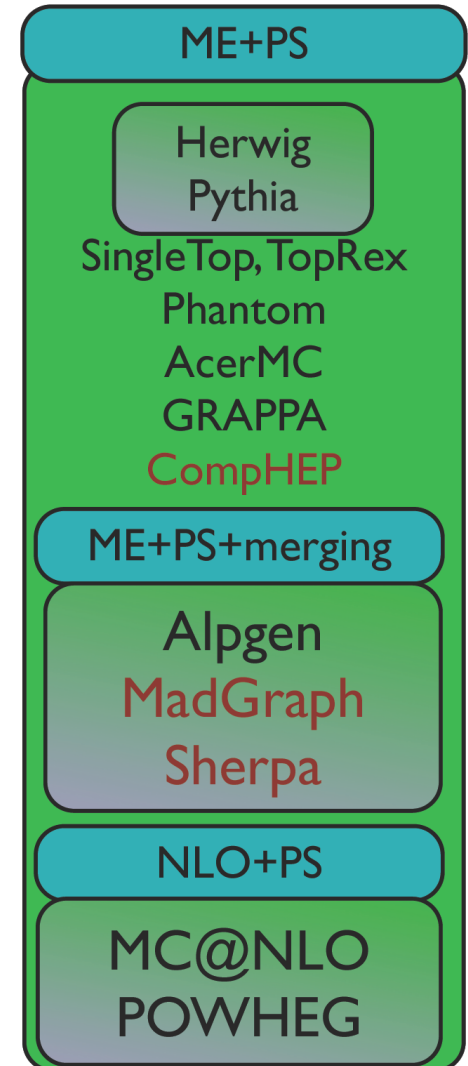
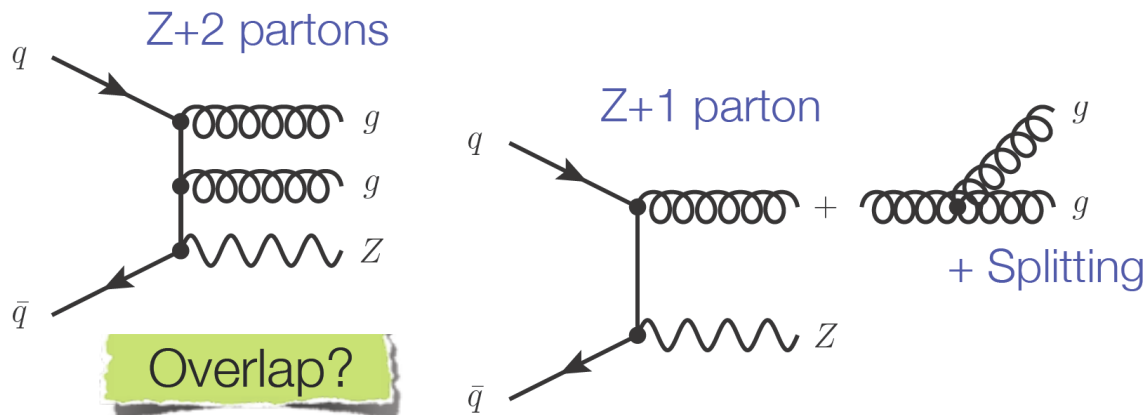
Type II : Leading order matrix element,
parton shower & **merging**

i.e.: MEs for $2 \rightarrow n$ 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]



[F. Maltoni]

Pythia sub-processes

No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess
Hard QCD processes:	36 $f_i \gamma \rightarrow f_k W^\pm$	New gauge bosons:	Higgs pairs:	Compositeness:	210 $f_i \bar{f}_j \rightarrow \bar{\ell}_L \bar{\nu}_\ell^* +$	250 $f_i g \rightarrow \bar{q}_i L \bar{\chi}_3$
11 $f_i \bar{f}_j \rightarrow f_k \bar{f}_k$	69 $\gamma \gamma \rightarrow W^+ W^-$	141 $f_i \bar{f}_i \rightarrow \gamma/Z^0/Z^0$	297 $f_i \bar{f}_j \rightarrow H^\pm h^0$	146 $e \gamma \rightarrow e^*$	211 $f_i \bar{f}_j \rightarrow \bar{\tau}_1 \bar{\nu}_\tau^* +$	251 $f_i g \rightarrow \bar{q}_i R \bar{\chi}_3$
12 $f_i \bar{f}_i \rightarrow f_k \bar{f}_k$	70 $\gamma W^\pm \rightarrow Z^0 W^\pm$	142 $f_i \bar{f}_j \rightarrow W^{+\mp}$	298 $f_i \bar{f}_j \rightarrow H^\pm H^0$	147 $d g \rightarrow d^*$	212 $f_i \bar{f}_j \rightarrow \bar{\tau}_2 \bar{\nu}_\tau^* +$	252 $f_i g \rightarrow \bar{q}_i L \bar{\chi}_4$
13 $f_i \bar{f}_i \rightarrow g g$	Prompt photons:	144 $f_i \bar{f}_j \rightarrow R$	299 $f_i \bar{f}_i \rightarrow A^0 h^0$	148 $u g \rightarrow u^*$	213 $f_i \bar{f}_i \rightarrow \bar{\nu}_\ell \bar{\nu}_\ell^* +$	253 $f_i g \rightarrow \bar{q}_i R \bar{\chi}_4$
28 $f_i g \rightarrow f_i g$	14 $f_i \bar{f}_i \rightarrow g \gamma$	Heavy SM Higgs:	300 $f_i \bar{f}_i \rightarrow A^0 H^0$	167 $q_i q_j \rightarrow d^* q_k$	214 $f_i \bar{f}_i \rightarrow \tilde{\nu}_\tau \tilde{\nu}_\tau^* +$	254 $f_i g \rightarrow \bar{q}_j L \bar{\chi}_1^\pm$
53 $g g \rightarrow f_k \bar{f}_k$	18 $f_i \bar{f}_i \rightarrow \gamma \gamma$	5 $Z^0 Z^0 \rightarrow h^0$	301 $f_i \bar{f}_i \rightarrow H^+ H^-$	168 $q_i q_j \rightarrow u^* q_k$	216 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_1$	256 $f_i g \rightarrow \bar{q}_j L \bar{\chi}_2^\pm$
68 $g g \rightarrow g g$	29 $f_i g \rightarrow f_i \gamma$	8 $W^+ W^- \rightarrow h^0$	Leptoquarks:	169 $q_i \bar{q}_i \rightarrow e^{\pm} e^{*\mp}$	217 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_2$	258 $f_i g \rightarrow \bar{q}_i L \tilde{g}$
Soft QCD processes:	114 $g g \rightarrow \gamma \gamma$	71 $Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0$	145 $q_i \bar{\ell}_j \rightarrow L_{Qj}$	165 $f_i \bar{f}_i (\rightarrow \gamma^*/Z^0) \rightarrow f_k \bar{f}_k$	218 $f_i \bar{f}_i \rightarrow \tilde{\chi}_3 \tilde{\chi}_3$	259 $f_i g \rightarrow \bar{q}_i R \tilde{g}$
91 elastic scattering	115 $g g \rightarrow g \gamma$	72 $Z_L^0 Z_L^0 \rightarrow W_L^+ W_L^-$	162 $q g \rightarrow \ell L_{Qj}$	166 $f_i \bar{f}_j (\rightarrow W^\pm) \rightarrow f_k \bar{f}_k$	219 $f_i \bar{f}_i \rightarrow \tilde{\chi}_4 \tilde{\chi}_4$	261 $f_i \bar{f}_i \rightarrow \tilde{t}_1 \tilde{t}_1$
92 single diffraction (XB)	Deeply Inel. Scatt.:	73 $Z_L^0 W_L^\pm \rightarrow Z_L^0 W_L^\pm$	163 $g g \rightarrow L_{Qj} \bar{L}_{Qj}$	Extra Dimensions:	220 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_2$	262 $f_i \bar{f}_i \rightarrow \tilde{t}_2 \tilde{t}_2^*$
93 single diffraction (AX)	10 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i$	76 $W_L^+ W_L^- \rightarrow Z_L^0 Z_L^0$	164 $q_i \bar{q}_i \rightarrow L_{Qj} \bar{L}_{Qj}$	391 $f \bar{f} \rightarrow G^*$	221 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_3$	263 $f_i \bar{f}_i \rightarrow \tilde{t}_1 \tilde{t}_2^* +$
94 double diffraction	99 $\gamma^* q \rightarrow q$	77 $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$	Technicolor:	392 $g g \rightarrow G^*$	222 $f_i \bar{f}_j \rightarrow \tilde{\chi}_1 \tilde{\chi}_4$	264 $g g \rightarrow \tilde{t}_1 \tilde{t}_1^*$
95 low- p_\perp production	Photon-induced:	BSM Neutral Higgs:	149 $g g \rightarrow \eta_{tc}$	393 $q \bar{q} \rightarrow G^*$	223 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_3$	265 $g g \rightarrow \tilde{t}_2 \tilde{t}_2^*$
Open heavy flavour: (also fourth generation)	33 $f_i \gamma \rightarrow f_i g$	151 $f_i \bar{f}_i \rightarrow H^0$	191 $f_i \bar{f}_i \rightarrow \rho_{tc}^0$	394 $q g \rightarrow G^*$	224 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_4$	271 $f_i \bar{f}_j \rightarrow \bar{q}_i L \bar{q}_j L$
81 $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$	34 $f_i \gamma \rightarrow f_i \gamma$	152 $g g \rightarrow H^0$	192 $f_i \bar{f}_j \rightarrow \rho_{tc}^+$	395 $g g \rightarrow G^*$	225 $f_i \bar{f}_i \rightarrow \tilde{\chi}_3 \tilde{\chi}_4$	272 $f_i \bar{f}_j \rightarrow \bar{q}_i R \bar{q}_j R$
82 $g g \rightarrow Q_k \bar{Q}_k$	54 $g \gamma \rightarrow f_k \bar{f}_k$	153 $\gamma \gamma \rightarrow H^0$	193 $f_i \bar{f}_i \rightarrow \omega_{tc}^0$	Left-right symmetry:	226 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$	273 $f_i \bar{f}_j \rightarrow \bar{q}_i L \bar{q}_j R +$
83 $q_i \bar{f}_j \rightarrow Q_k \bar{f}_i$	58 $\gamma \gamma \rightarrow f_k \bar{f}_k$	171 $f_i \bar{f}_i \rightarrow Z^0 H^0$	194 $f_i \bar{f}_i \rightarrow f_k \bar{f}_k$	341 $\ell_i \bar{\ell}_j \rightarrow H_L^{\pm\pm}$	227 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$	274 $f_i \bar{f}_j \rightarrow \bar{q}_i L \bar{q}_j L$
84 $g \gamma \rightarrow Q_k \bar{Q}_k$	131 $f_i \gamma \tilde{T}^* \rightarrow f_i g$	172 $f_i \bar{f}_j \rightarrow W^\pm H^0$	195 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i$	342 $\ell_i \bar{\ell}_j \rightarrow H_R^{\pm\pm}$	228 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$	275 $f_i \bar{f}_j \rightarrow \bar{q}_i R \bar{q}_j R$
85 $\gamma \gamma \rightarrow F_k \bar{F}_k$	132 $f_i \gamma \tilde{L}^* \rightarrow f_i g$	173 $f_i \bar{f}_j \rightarrow f_i f_j H^0$	361 $f_i \bar{f}_i \rightarrow W_L^+ W_L^-$	343 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$	229 $f_i \bar{f}_j \rightarrow \tilde{\chi}_1 \tilde{\chi}_1^\pm$	276 $f_i \bar{f}_j \rightarrow \bar{q}_i L \bar{q}_j R +$
Closed heavy flavour:	133 $f_i \gamma \tilde{T}^* \rightarrow f_i \gamma$	174 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i H^0$	362 $f_i \bar{f}_i \rightarrow W_L^\pm \pi_{tc}^\mp$	344 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$	230 $f_i \bar{f}_j \rightarrow \tilde{\chi}_2 \tilde{\chi}_1^\pm$	277 $f_i \bar{f}_i \rightarrow \bar{q}_j L \bar{q}_j L$
86 $g g \rightarrow J/\psi g$	134 $f_i \gamma \tilde{L}^* \rightarrow f_i \gamma$	181 $g g \rightarrow Q_k \bar{Q}_k H^0$	363 $f_i \bar{f}_i \rightarrow \pi_{tc}^+ \pi_{tc}^-$	345 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \mu^\mp$	231 $f_i \bar{f}_j \rightarrow \tilde{\chi}_3 \tilde{\chi}_1^\pm$	278 $f_i \bar{f}_i \rightarrow \bar{q}_j R \bar{q}_j R$
87 $g g \rightarrow \chi_{0c} g$	135 $g \gamma \tilde{T}^* \rightarrow f_i \bar{f}_i$	182 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k H^0$	364 $f_i \bar{f}_i \rightarrow \gamma \pi_{tc}^0$	346 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \mu^\mp$	232 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_1^\pm$	279 $g g \rightarrow \bar{q}_i L \bar{q}_i L$
88 $g g \rightarrow \chi_{1c} g$	136 $g \gamma \tilde{L}^* \rightarrow f_i \bar{f}_i$	183 $f_i \bar{f}_i \rightarrow g h^0$	365 $f_i \bar{f}_i \rightarrow \gamma \pi_{tc}^{0'}$	347 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \tau^\mp$	233 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_2^\pm$	280 $g g \rightarrow \bar{q}_i R \bar{q}_i R$
89 $g g \rightarrow \chi_{2c} g$	137 $\gamma \tilde{T}^* \gamma \tilde{T}^* \rightarrow f_i \bar{f}_i$	184 $f_i g \rightarrow f_i H^0$	366 $f_i \bar{f}_i \rightarrow Z^0 \pi_{tc}^{0'}$	348 $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \tau^\mp$	234 $f_i \bar{f}_j \rightarrow \tilde{\chi}_2 \tilde{\chi}_2^\pm$	281 $b q_i \rightarrow \bar{b}_1 \bar{q}_i L$
104 $g g \rightarrow \chi_{0c}$	138 $\gamma \tilde{T}^* \gamma_L^* \rightarrow f_i \bar{f}_i$	185 $g g \rightarrow g H^0$	367 $f_i \bar{f}_i \rightarrow Z^0 \pi_{tc}^{0'}$	349 $f_i \bar{f}_i \rightarrow H_L^+ H_L^-$	235 $f_i \bar{f}_j \rightarrow \tilde{\chi}_3 \tilde{\chi}_2^\pm$	282 $b q_i \rightarrow \bar{b}_2 \bar{q}_i R$
105 $g g \rightarrow \chi_{2c}$	139 $\gamma \tilde{L}^* \gamma \tilde{T}^* \rightarrow f_i \bar{f}_i$	156 $f_i \bar{f}_i \rightarrow A^0$	368 $f_i \bar{f}_i \rightarrow W^\pm \pi_{tc}^\mp$	350 $f_i \bar{f}_i \rightarrow H_R^+ H_R^-$	236 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_2^\pm$	283 $b q_i \rightarrow \bar{b}_1 \bar{q}_i R +$
106 $g g \rightarrow J/\psi \gamma$	140 $\gamma \tilde{L}^* \gamma_L^* \rightarrow f_i \bar{f}_i$	157 $g g \rightarrow A^0$	370 $f_i \bar{f}_j \rightarrow W_L^\pm Z_L^0$	351 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i H_L^{\pm\pm}$	237 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_1$	284 $b \bar{q}_i \rightarrow \bar{b}_1 \bar{q}_i L$
107 $g \gamma \rightarrow J/\psi g$	80 $q_i \gamma \rightarrow q_k \pi^\pm$	158 $\gamma \gamma \rightarrow A^0$	371 $f_i \bar{f}_j \rightarrow W_L^\pm \pi_{tc}^0$	352 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i H_R^{\pm\pm}$	238 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_2$	285 $b \bar{q}_i \rightarrow \bar{b}_2 \bar{q}_i R$
108 $\gamma \gamma \rightarrow J/\psi \gamma$	Light SM Higgs:	176 $f_i \bar{f}_i \rightarrow Z^0 A^0$	372 $f_i \bar{f}_j \rightarrow \pi_{tc}^\pm Z_L^0$	353 $f_i \bar{f}_i \rightarrow Z^0 R$	239 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_3$	286 $b \bar{q}_i \rightarrow \bar{b}_1 \bar{q}_i R +$
W/Z production:	3 $f_i \bar{f}_i \rightarrow h^0$	177 $f_i \bar{f}_j \rightarrow W^\pm A^0$	373 $f_i \bar{f}_j \rightarrow \pi_{tc}^\pm \pi_{tc}^0$	354 $f_i \bar{f}_j \rightarrow W_R^\pm$	240 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_4$	287 $f_i \bar{f}_i \rightarrow \bar{b}_1 \tilde{b}_1^*$
1 $f_i \bar{f}_i \rightarrow \gamma^*/Z^0$	24 $f_i \bar{f}_i \rightarrow Z^0 h^0$	178 $f_i \bar{f}_j \rightarrow f_i f_j A^0$	374 $f_i \bar{f}_j \rightarrow \gamma \pi_{tc}^\pm$	SUSY:	241 $f_i \bar{f}_j \rightarrow \tilde{g} \tilde{\chi}_1^\pm$	288 $f_i \bar{f}_i \rightarrow \bar{b}_2 \tilde{b}_2^*$
2 $f_i \bar{f}_j \rightarrow W^\pm$	26 $f_i \bar{f}_j \rightarrow W^\pm h^0$	179 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i A^0$	375 $f_i \bar{f}_j \rightarrow Z^0 \pi_{tc}^\pm$	201 $f_i \bar{f}_i \rightarrow \tilde{\ell}_L \tilde{\ell}_L^*$	242 $f_i \bar{f}_j \rightarrow \tilde{g} \tilde{\chi}_2^\pm$	289 $g g \rightarrow \bar{b}_1 \tilde{b}_1^*$
22 $f_i \bar{f}_i \rightarrow Z^0 Z^0$	32 $f_i g \rightarrow f_i h^0$	186 $g g \rightarrow Q_k \bar{Q}_k A^0$	376 $f_i \bar{f}_j \rightarrow W^\pm \pi_{tc}^{0'}$	202 $f_i \bar{f}_i \rightarrow \tilde{e}_R \tilde{e}_R^*$	243 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_2^\pm$	290 $g g \rightarrow \bar{b}_2 \tilde{b}_2^*$
23 $f_i \bar{f}_j \rightarrow Z^0 W^\pm$	102 $g g \rightarrow h^0$	187 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k A^0$	377 $f_i \bar{f}_j \rightarrow W^\pm \pi_{tc}^{0'}$	203 $f_i \bar{f}_i \rightarrow \tilde{e}_L \tilde{e}_R^* +$	244 $g g \rightarrow \tilde{g} \tilde{g}$	291 $bb \rightarrow \tilde{b}_1 \tilde{b}_1$
25 $f_i \bar{f}_i \rightarrow W^+ W^-$	103 $\gamma \gamma \rightarrow h^0$	188 $f_i \bar{f}_i \rightarrow g A^0$	381 $q_i \bar{q}_j \rightarrow q_i q_j$	204 $f_i \bar{f}_i \rightarrow \tilde{\mu}_L \tilde{\mu}_L^*$	246 $f_i g \rightarrow \bar{q}_i L \tilde{\chi}_1$	292 $bb \rightarrow \tilde{b}_2 \tilde{b}_2$
25 $f_i \bar{f}_i \rightarrow g Z^0$	110 $f_i \bar{f}_i \rightarrow \gamma h^0$	189 $f_i g \rightarrow f_i A^0$	382 $q_i \bar{q}_i \rightarrow q_k \bar{q}_k$	205 $f_i \bar{f}_i \rightarrow \tilde{\mu}_R \tilde{\mu}_R^* +$	247 $f_i g \rightarrow \bar{q}_i R \tilde{\chi}_1$	293 $bb \rightarrow \tilde{b}_1 \tilde{b}_2$
16 $f_i \bar{f}_j \rightarrow g W^\pm$	111 $f_i g \rightarrow g h^0$	190 $g g \rightarrow g A^0$	383 $q_i \bar{q}_i \rightarrow g g$	206 $f_i \bar{f}_i \rightarrow \tilde{\mu}_L \tilde{\mu}_R^* +$	248 $f_i g \rightarrow \bar{q}_i L \tilde{\chi}_2^*$	294 $bg \rightarrow \tilde{b}_1 \tilde{g}$
30 $f_i g \rightarrow f_i Z^0$	112 $f_i g \rightarrow f_i h^0$	Charged Higgs:	384 $f_i g \rightarrow f_i g$	207 $f_i \bar{f}_i \rightarrow \tilde{\tau}_1 \tilde{\tau}_1^*$	249 $f_i g \rightarrow \bar{q}_i R \tilde{\chi}_2$	295 $bg \rightarrow \tilde{b}_2 \tilde{g}$
31 $f_i g \rightarrow f_k W^\pm$	113 $g g \rightarrow g h^0$	143 $f_i \bar{f}_j \rightarrow H^+$	385 $g g \rightarrow q_k \bar{q}_k$	208 $f_i \bar{f}_i \rightarrow \tilde{\tau}_2 \tilde{\tau}_2^*$		296 $bb \rightarrow \tilde{b}_1 \tilde{b}_2^* +$
19 $f_i \bar{f}_i \rightarrow \gamma Z^0$	121 $g g \rightarrow Q_k \bar{Q}_k h^0$	161 $f_i g \rightarrow f_k H^+$	386 $g g \rightarrow g g$	209 $f_i \bar{f}_i \rightarrow \tilde{\tau}_1 \tilde{\tau}_2^* +$		
20 $f_i \bar{f}_i \rightarrow \gamma Z^0$	122 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k h^0$	401 $g g \rightarrow \bar{t} b H^+$	387 $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$			
21 $f_i \bar{f}_j \rightarrow \gamma W^\pm$	123 $f_i \bar{f}_j \rightarrow f_i f_j h^0$	402 $q \bar{q} \rightarrow \bar{t} b H^+$	388 $g g \rightarrow Q_k \bar{Q}_k$			
35 $f_i \gamma \rightarrow f_i Z^0$	124 $f_i \bar{f}_j \rightarrow f_k \bar{f}_i h^0$					

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:

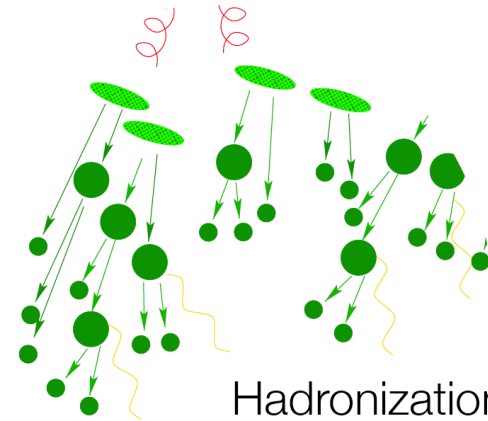
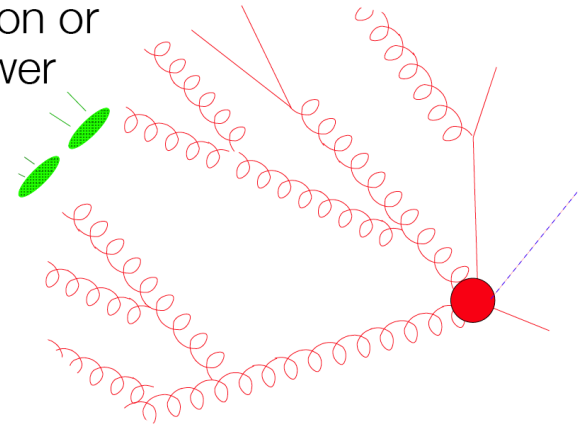
Parton shower forms hadrons

[non-perturbative, only models]

Decay of unstable hadrons

[perturbative QCD, electroweak theory]

Fragmentation or
Parton Shower



Hadronization &
Decays

Detector simulation

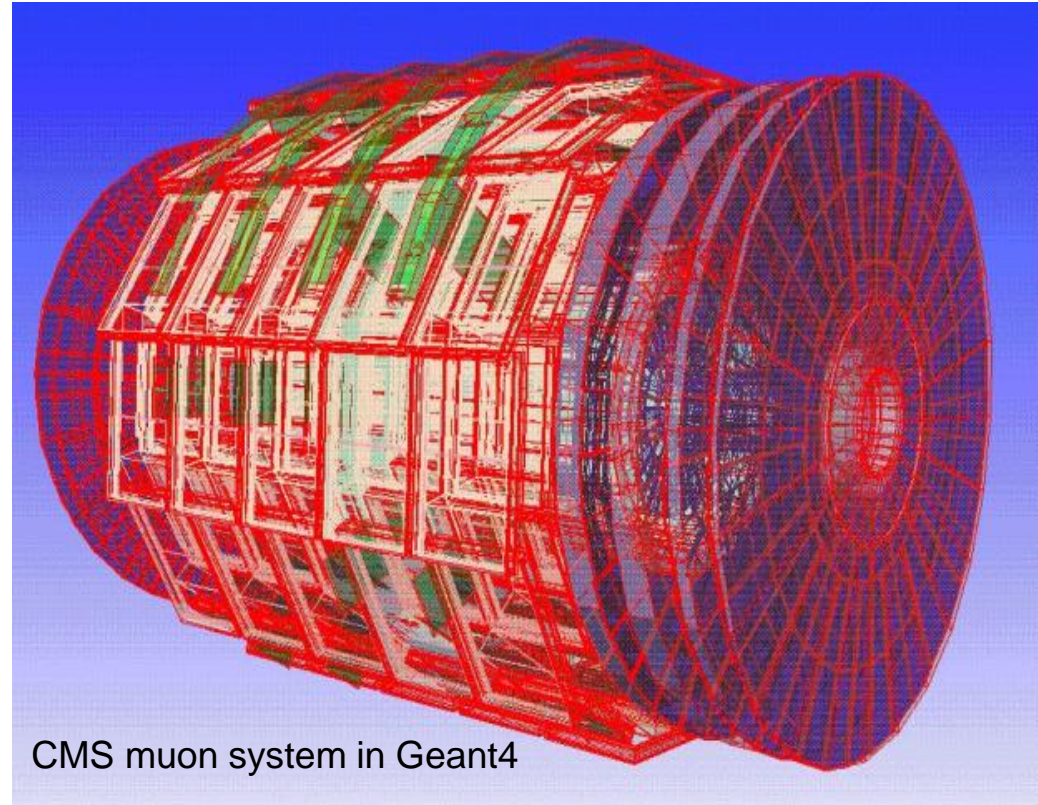
GEANT

Geometry And Tracking

Detailed description of
detector **geometry**
[sensitive & insensitive volumes]

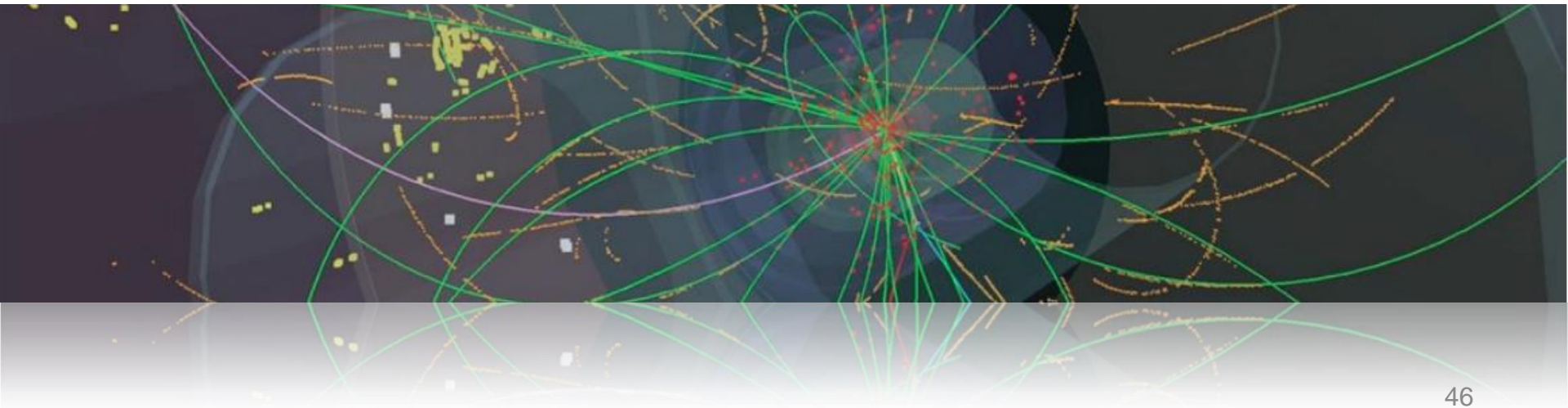
Tracking of all particles through
detector material ...

→ **Detector response**



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

Luminosity and cross-section measurements



Cross section & Luminosity

Number of observed events

just count ...

Background

measured from data or
calculated from theory

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L} dt \cdot \epsilon}$$

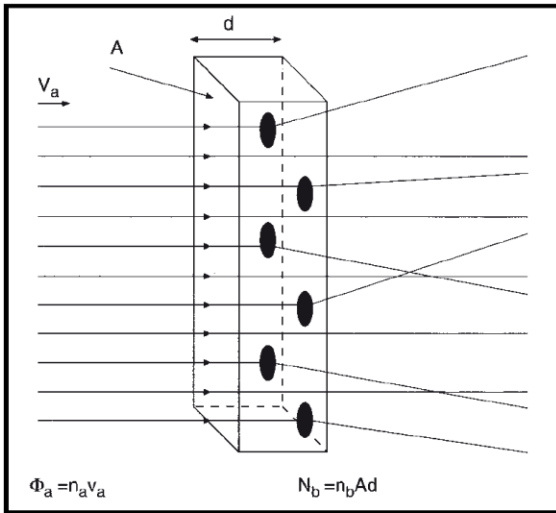
Luminosity

determined by accelerator,
triggers, ...

Efficiency

many factors, optimized
by experimentalist

Cross section & Luminosity



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

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

Collider experiment:

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

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

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

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

LHC:

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

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:

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

LHC Examples:

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

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

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

Elastic scattering in Coulomb region ...

Combination of the above ...

Accuracy: 10%

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

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

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

TOTEM

Accuracy: 2-3%

Relative Methods:

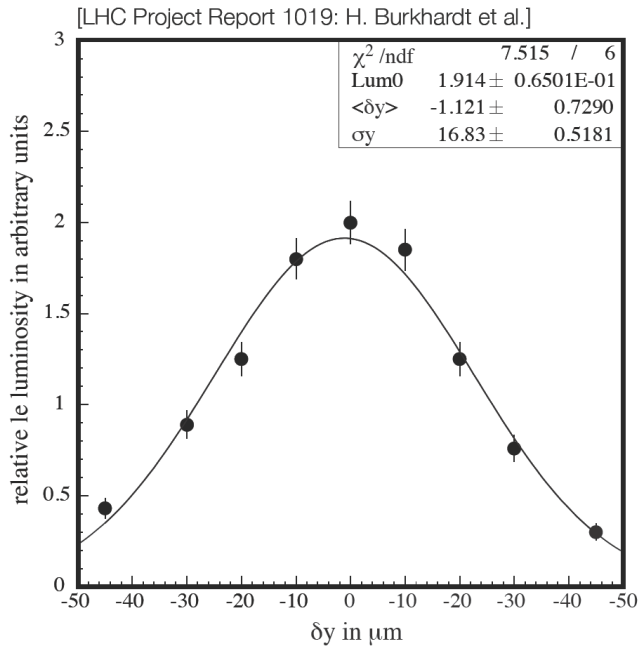
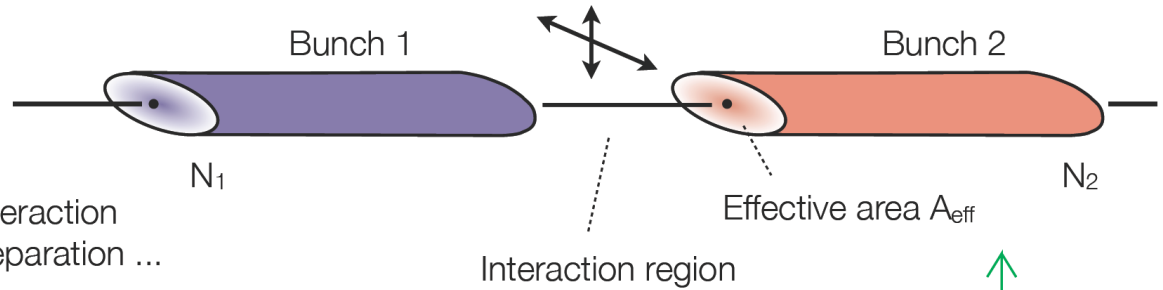
Particle counting; **LUCID @ ATLAS; HF, Pixels @ CMS**
[needs to be calibrated for absolute luminosity]

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

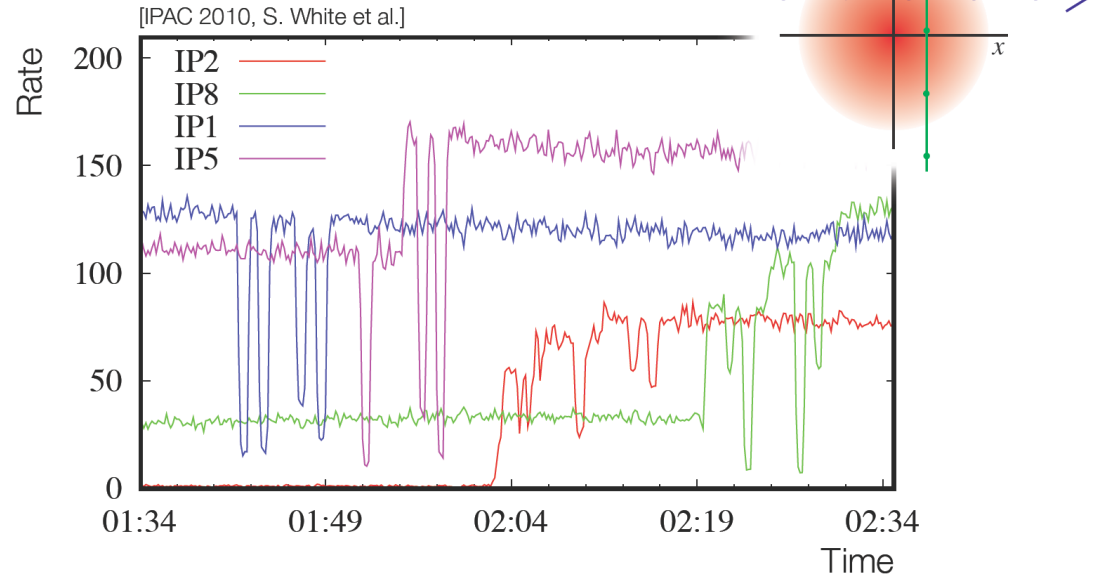
Van-der-Meer separation scan

Determine beam size ...

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



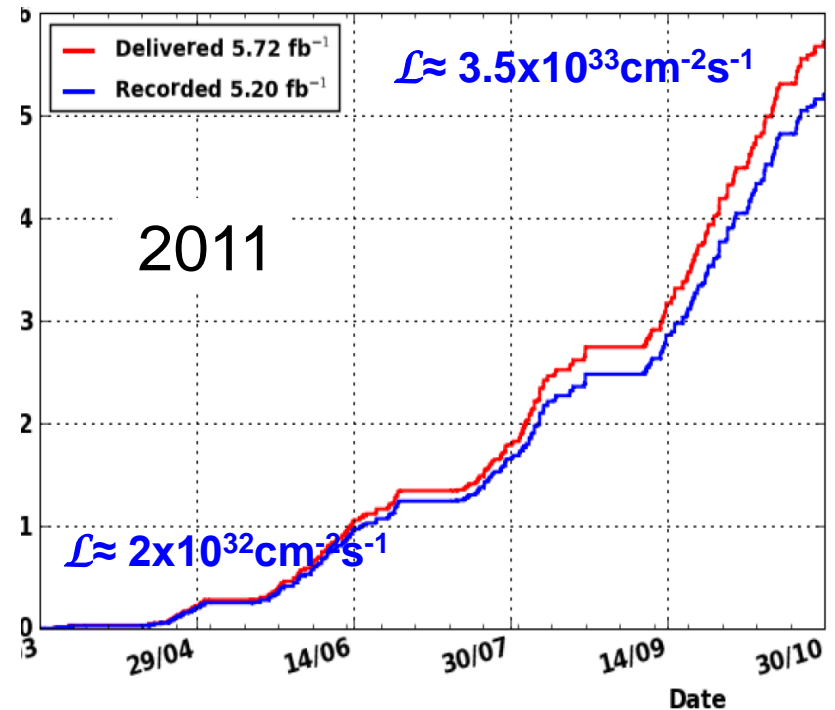
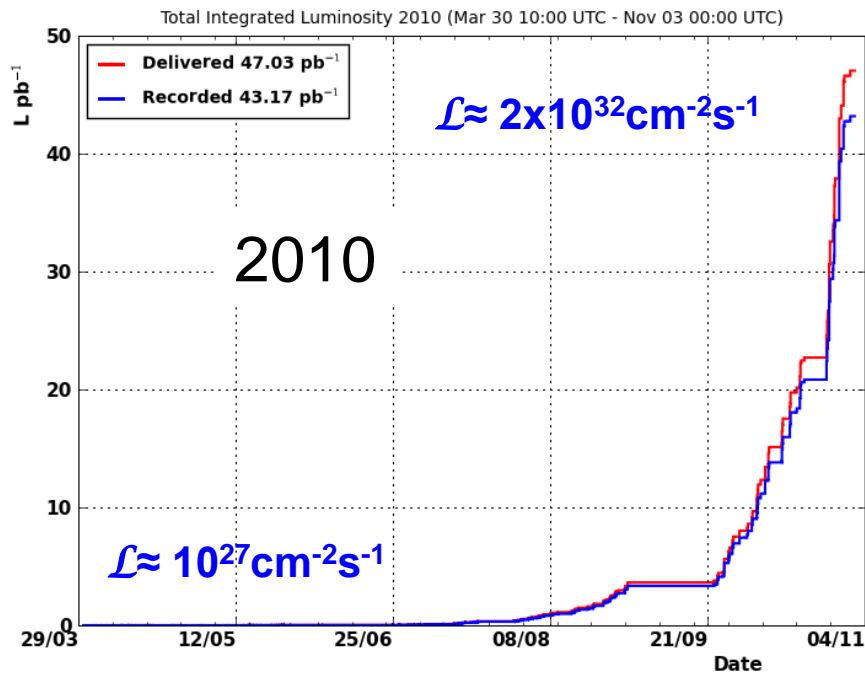
$$\frac{L}{L_0} = \exp \left[- \left(\frac{\delta_x}{2\sigma_x} \right)^2 - \left(\frac{\delta_y}{2\sigma_y} \right)^2 \right]$$



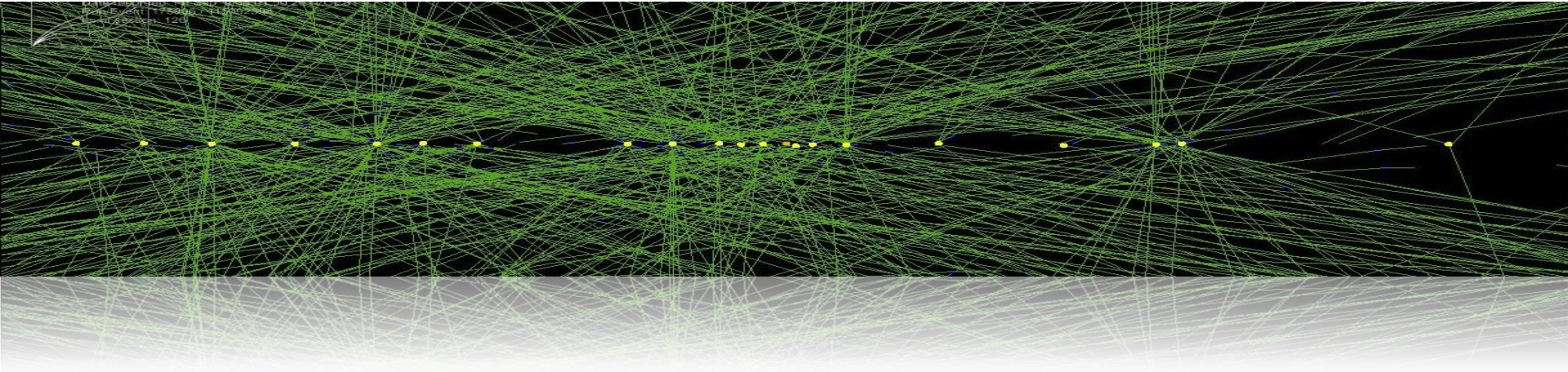
First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].

Instantaneous and integrated Luminosity

	Instantaneous (max)	Integrated
2010:	$2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	47 pb ⁻¹
2011:	$3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	5.7 fb ⁻¹



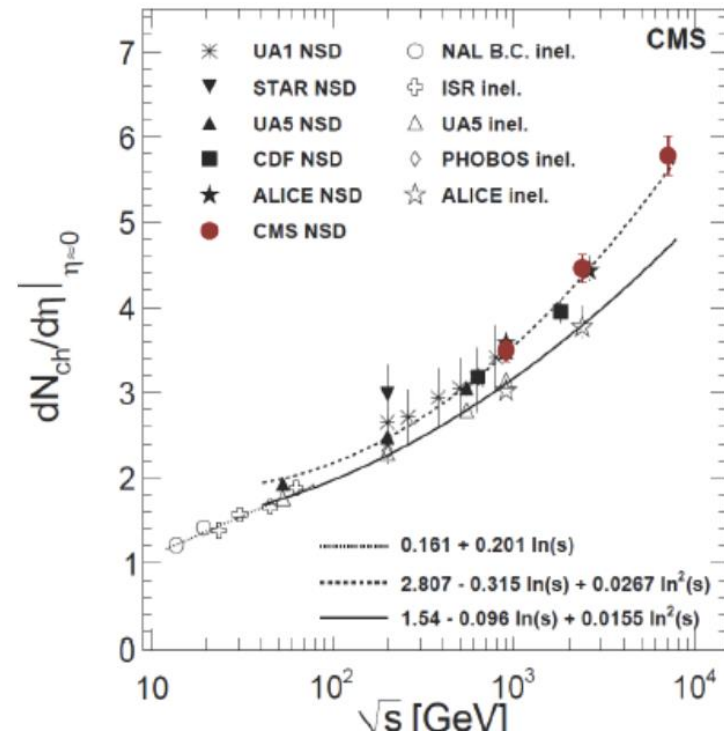
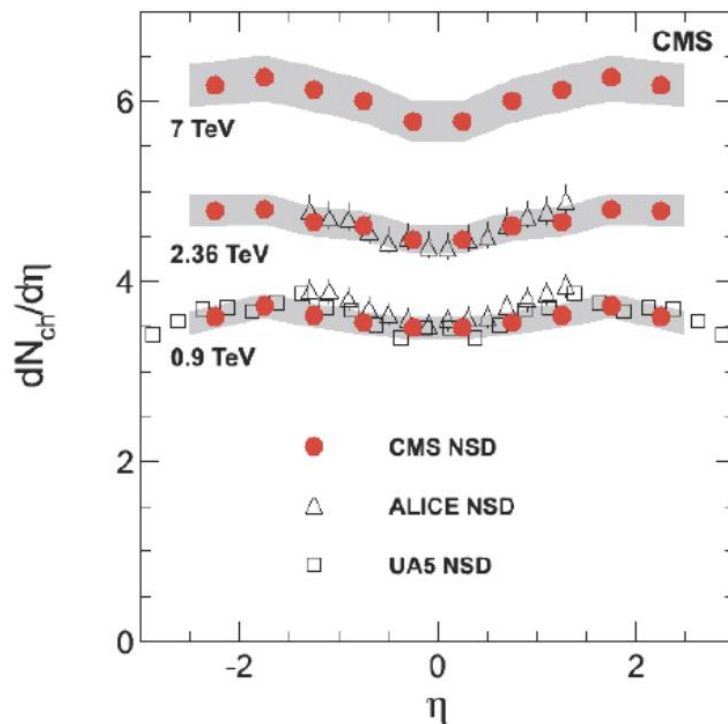
Minimum bias events



Characteristics of inelastic p-p collisions

Particle density in minimum bias events

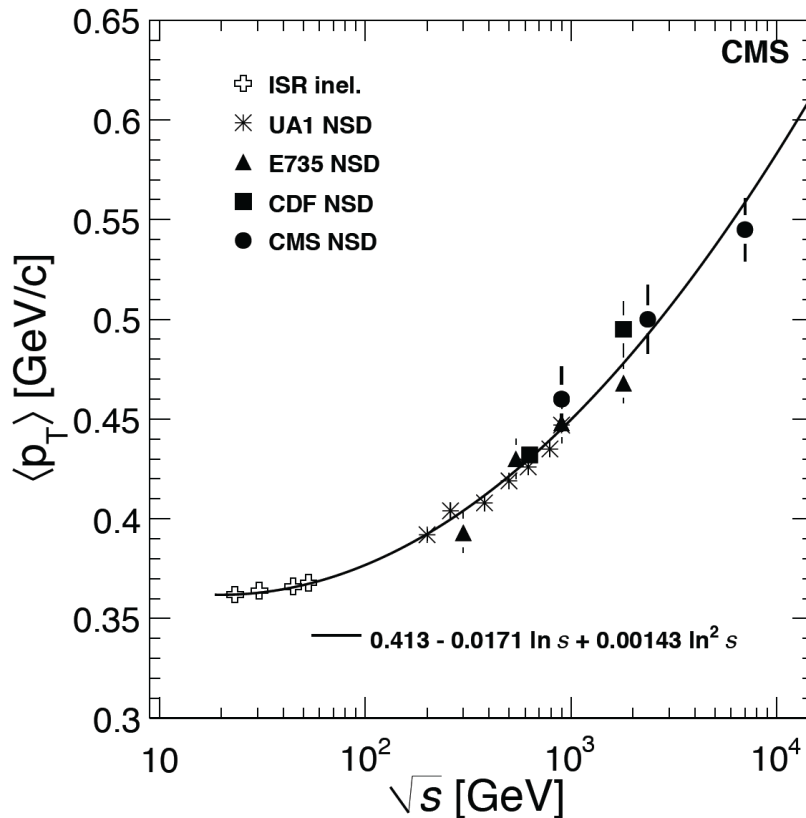
Soft QCD (PT threshold on tracks: 50 MeV)



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

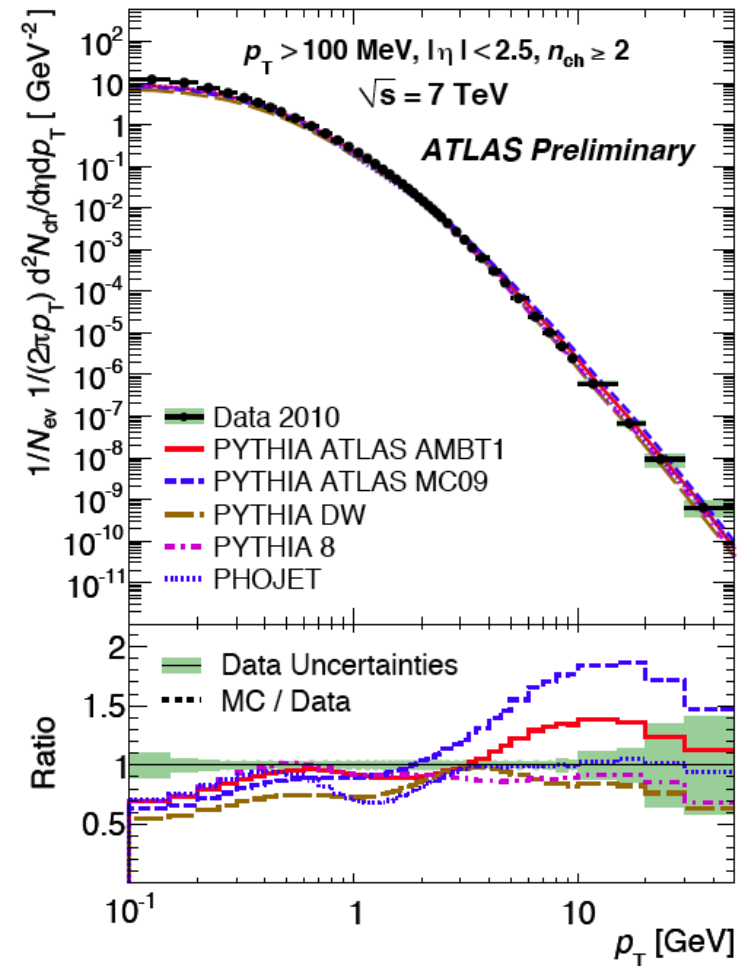
Charged particle p_T spectrum

$\langle p_T \rangle = 0.545$
 ± 0.005 (stat.)
 ± 0.015 (syst.) GeV/c

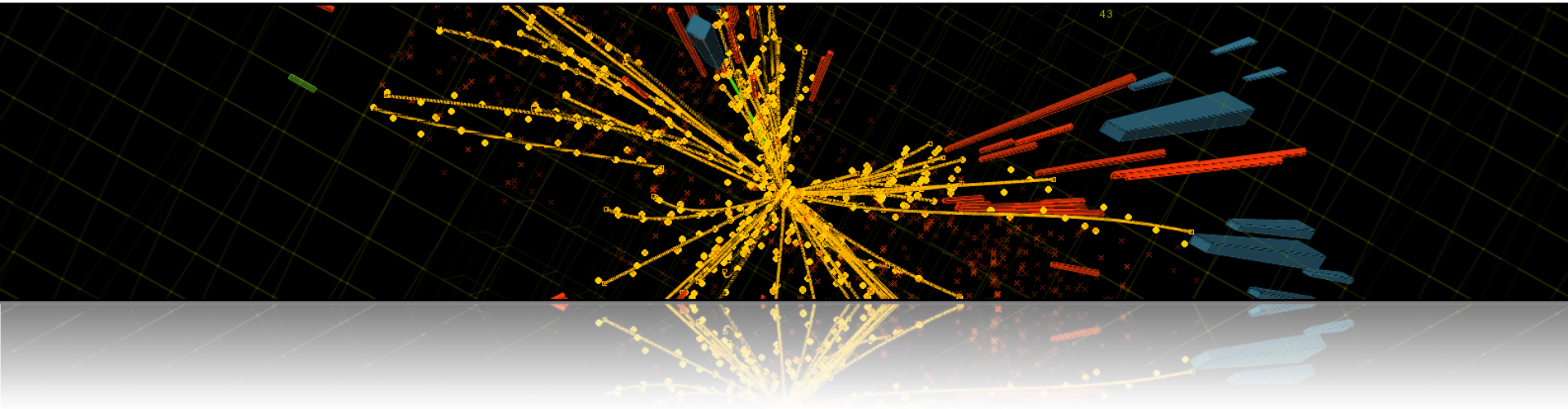


dN_{ch}/dp_T

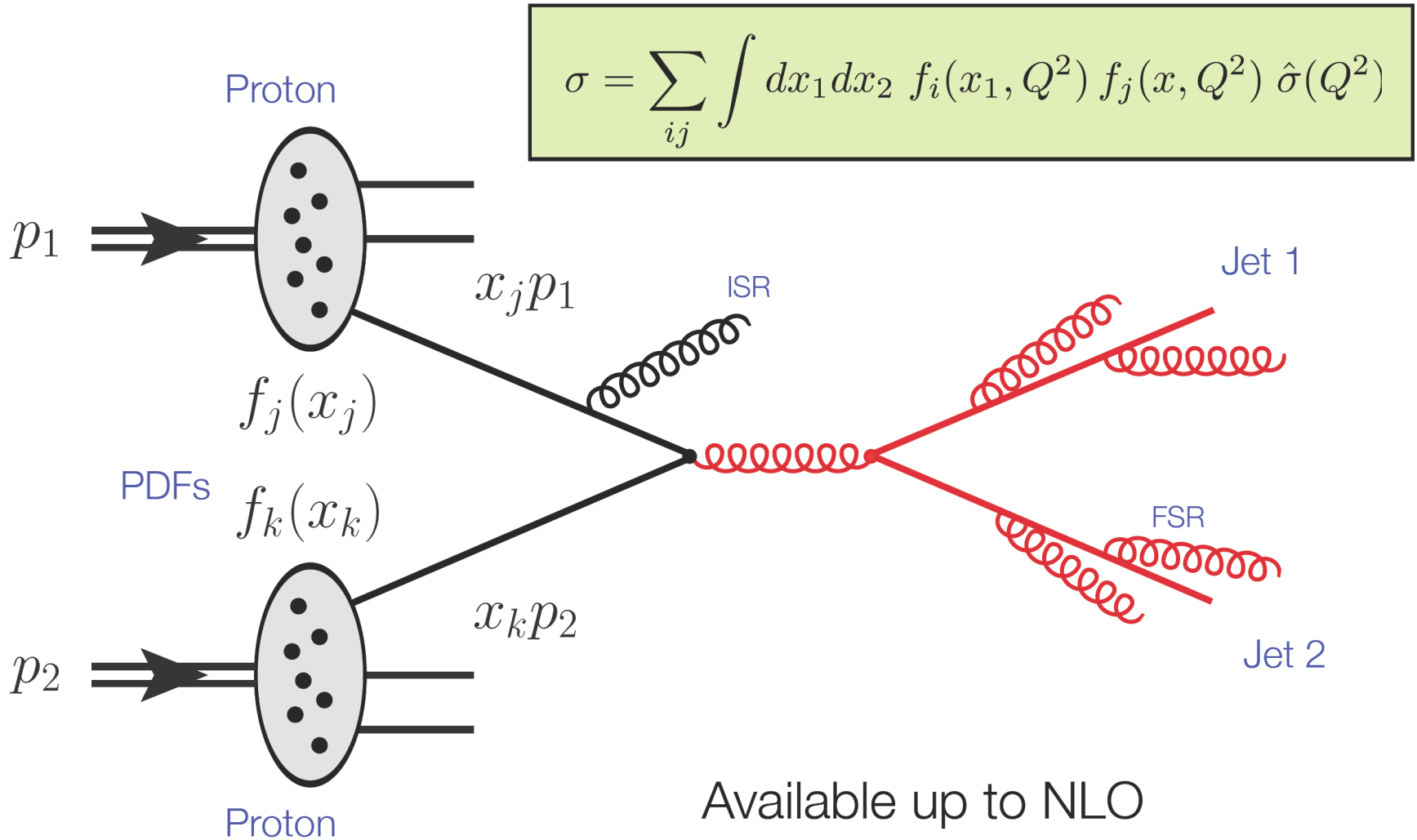
$p_T > 100$ MeV
 $|\eta| < 2.5$
 $N_{ch} \geq 2$



Jet physics



Jet production @ LHC



$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(Q^2)$$

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

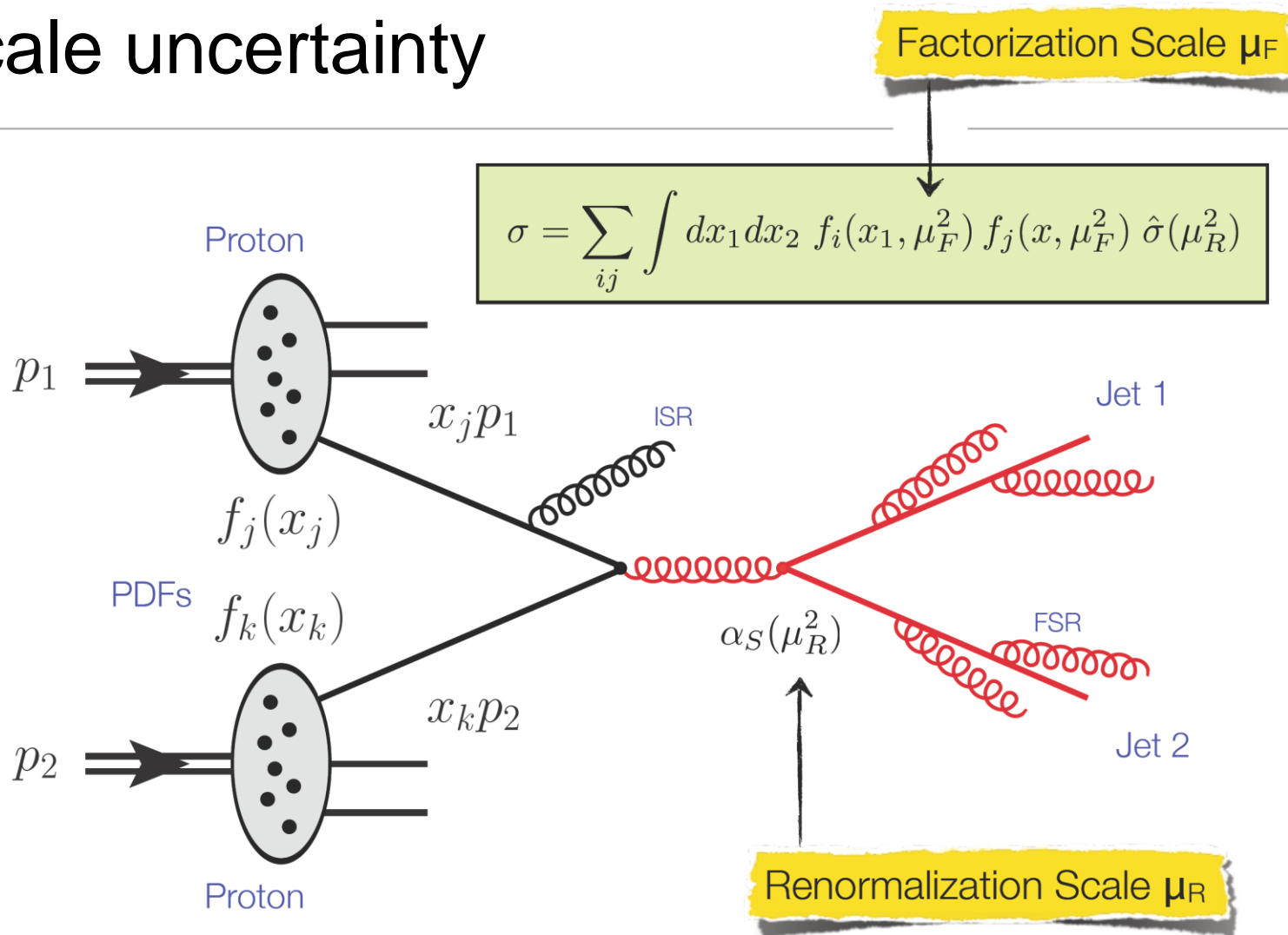
Solution: **renormalization**; choice of correct scale ...

[“Status of peaceful coexistence with divergences”, S.D. Drell]

Infrared (IR) divergences, i.e. at very **small** momenta

Solution: cancellations, factorization, IR-safe observables

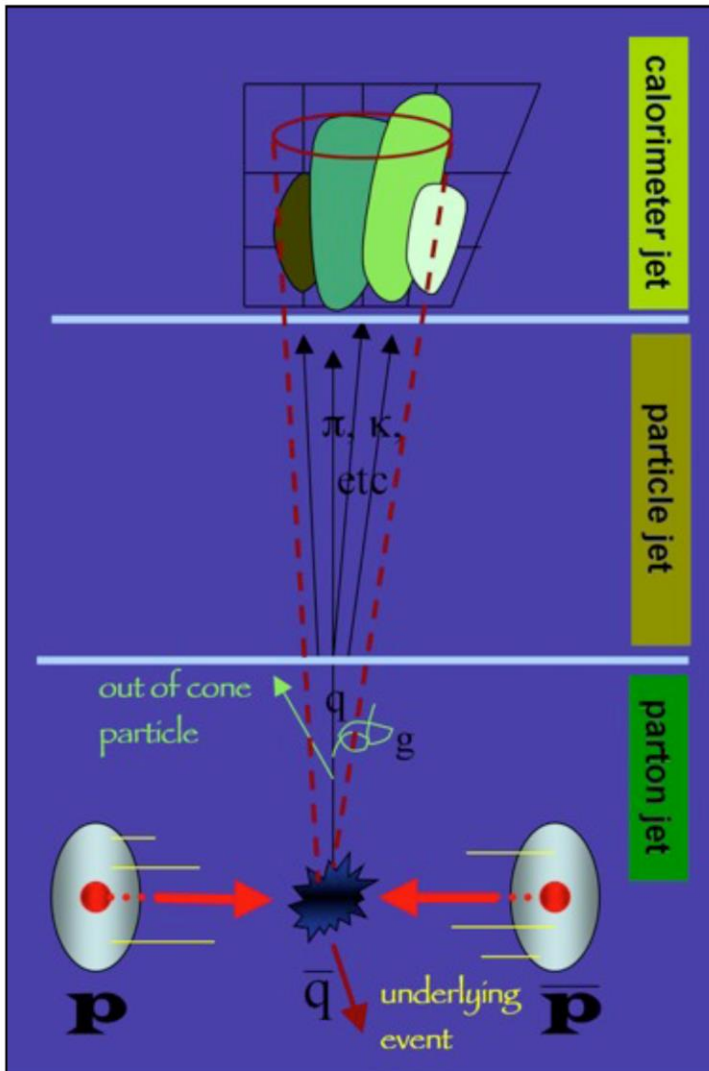
Scale uncertainty



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

Hadron Jet

[might include electrons, muons ...]

Hadronization
 Fragmentation
 Parton shower
 Particle decays

Parton Jet

[quarks and gluons]

Proton-proton interactions
 Initial and final state radiation
 Underlying event

“Measurement”



Jet

“Theory”

From measured energy to particle energy

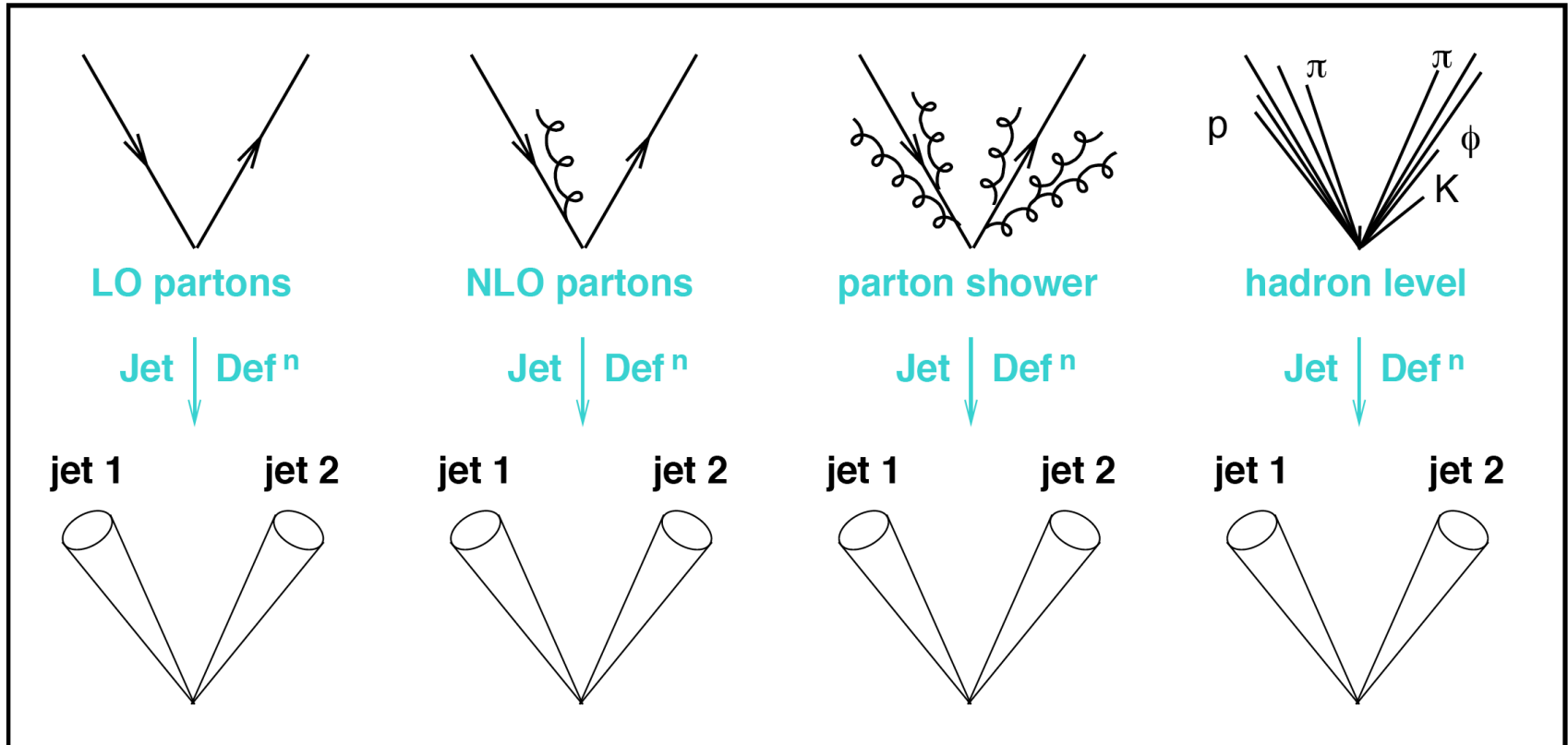
Compensate energy loss due to neutrinos, nuclear excitation ...

From particle energy to original parton energy

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

Needs Calibration

Jet properties measurement



Jets may look different at different levels
Robust jet definition \rightarrow 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:

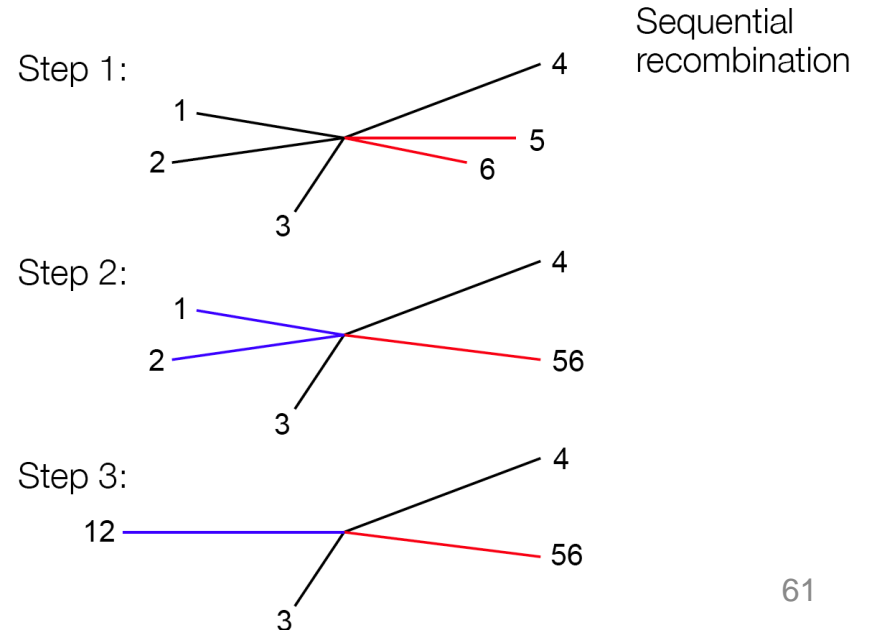
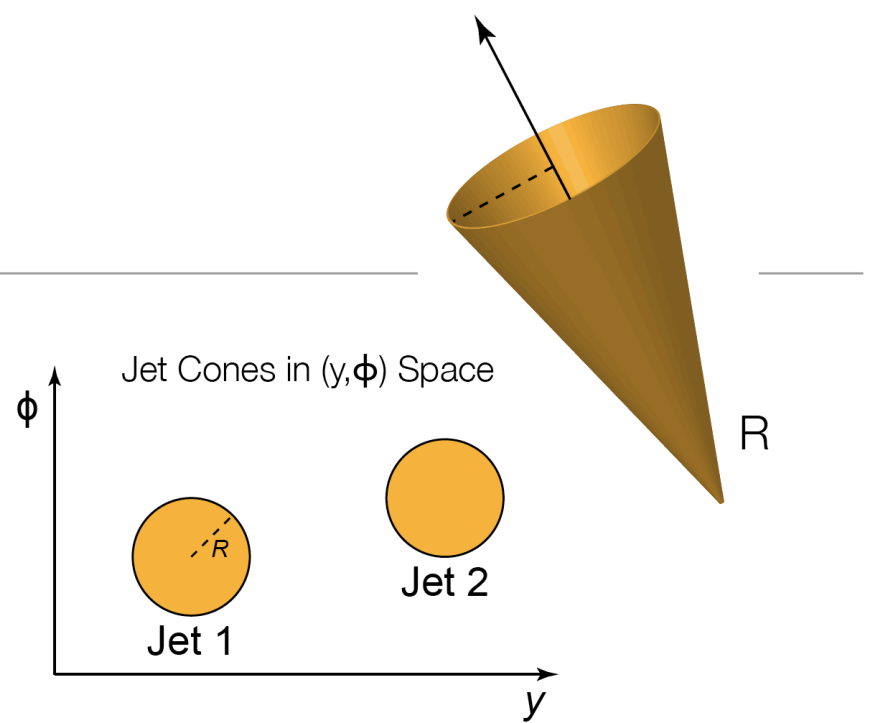
$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$

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]

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



Jet algorithms performance

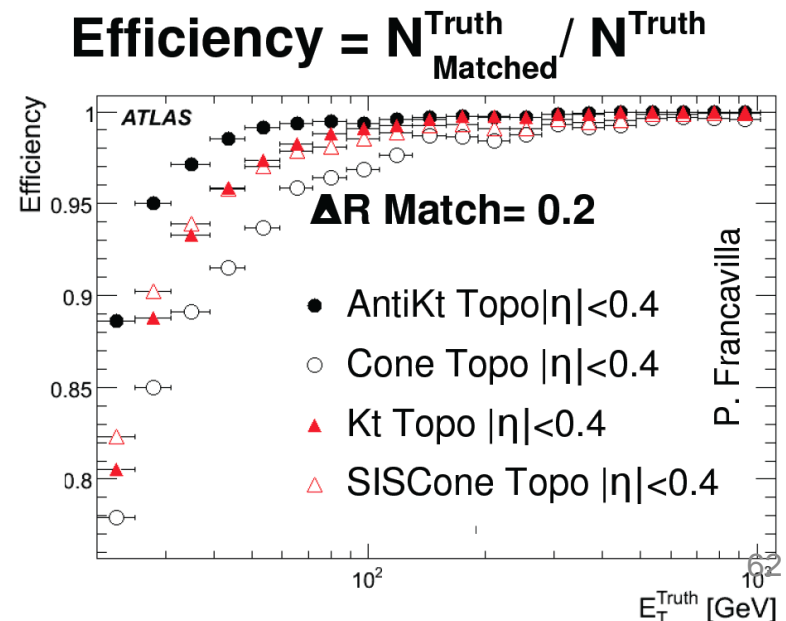
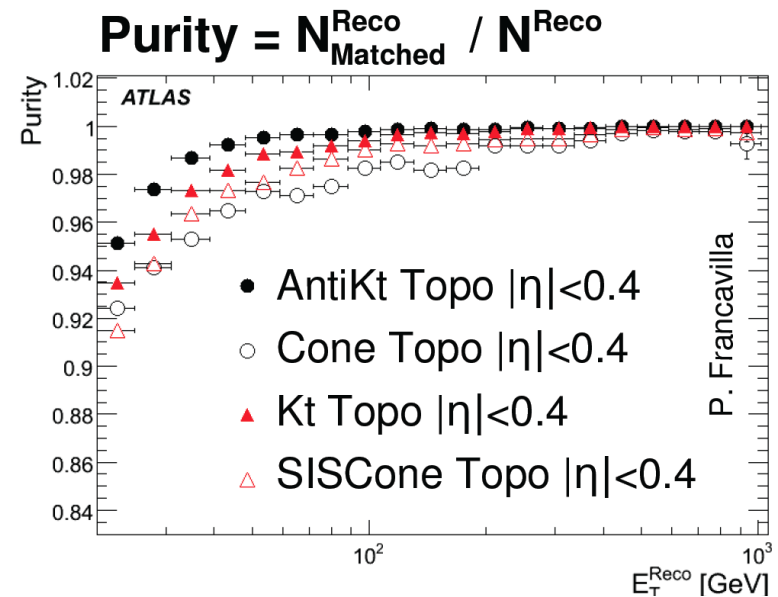
Anti-kt clustering algorithm:

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

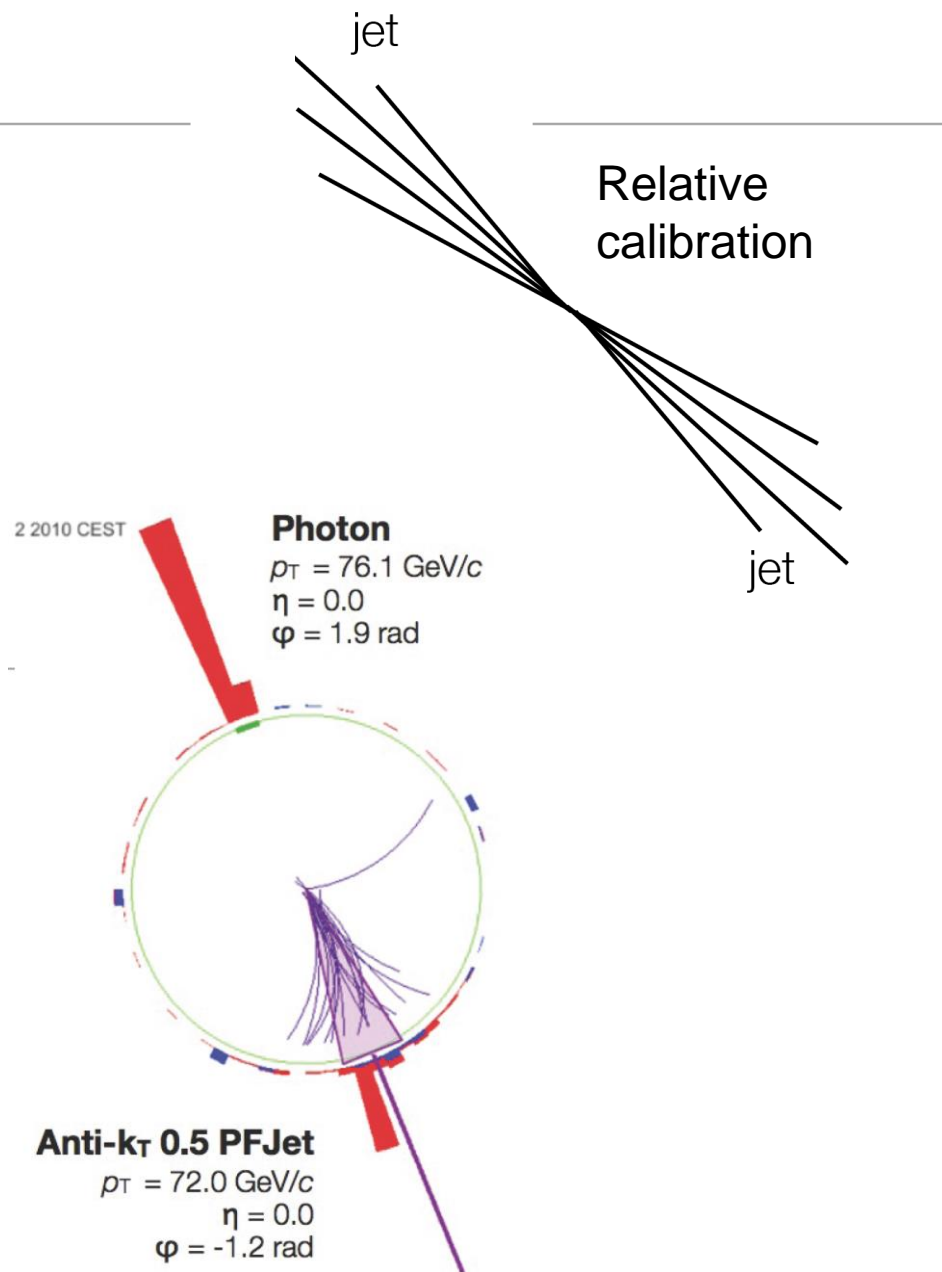
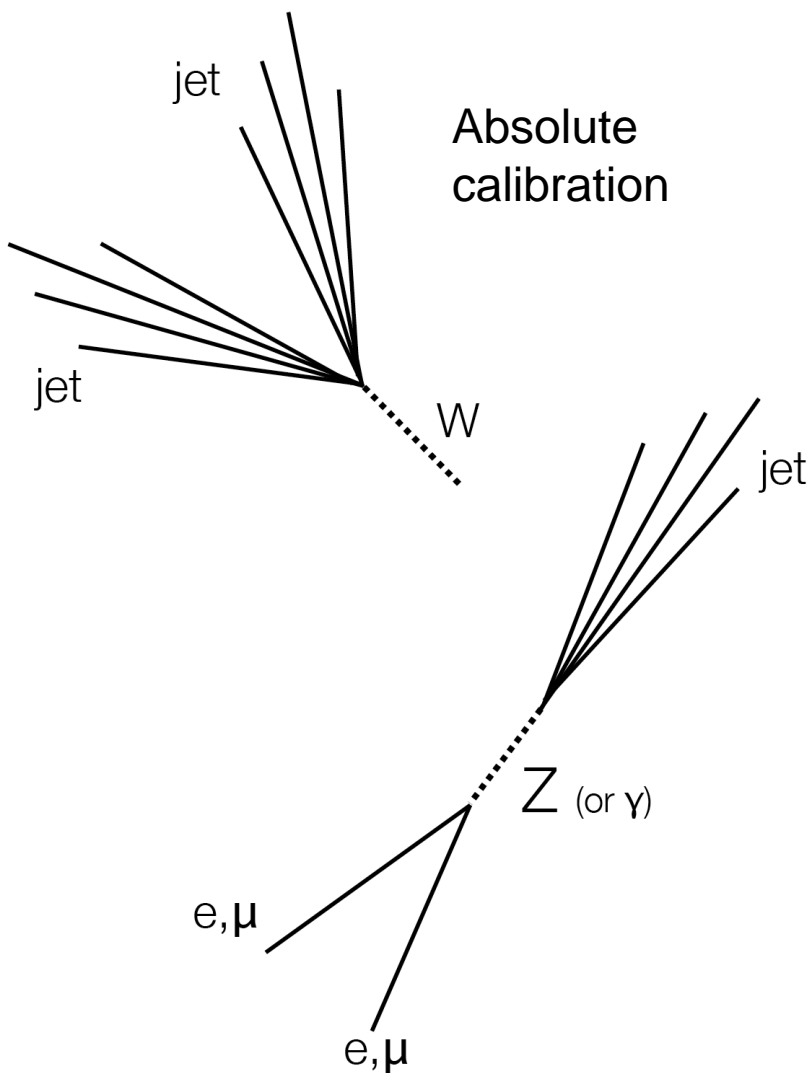
$p=1$: standard Kt

$p=-1$: anti-Kt

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



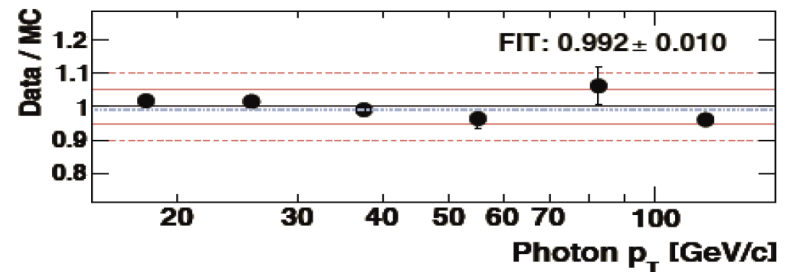
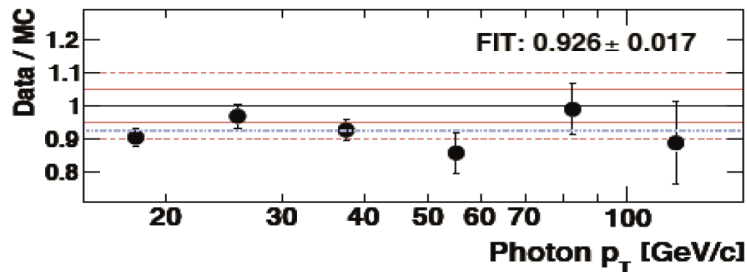
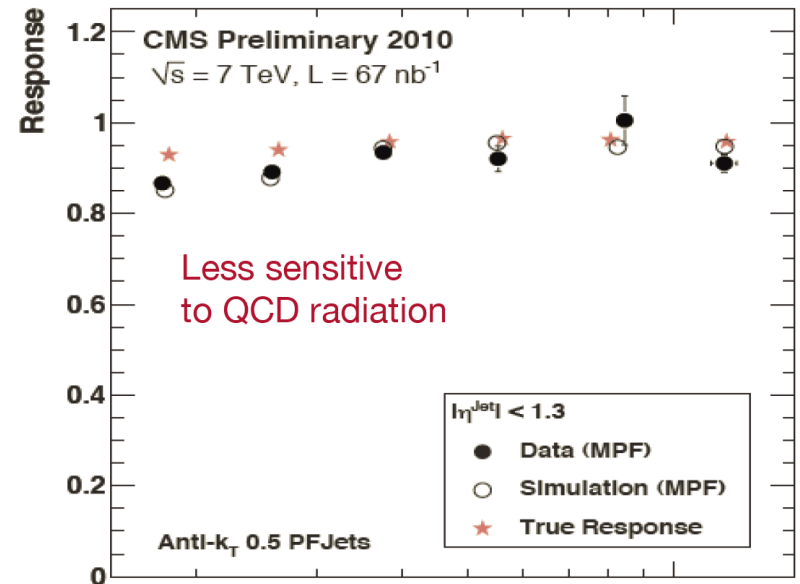
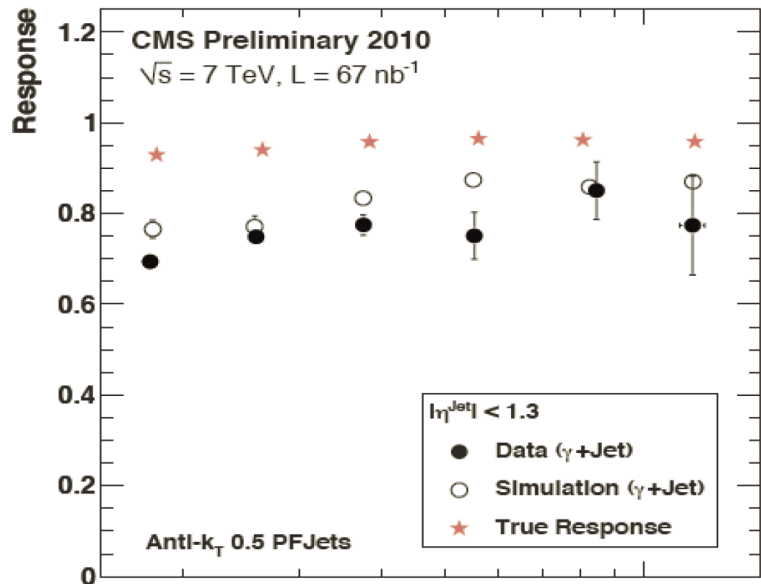
Jet energy calibration



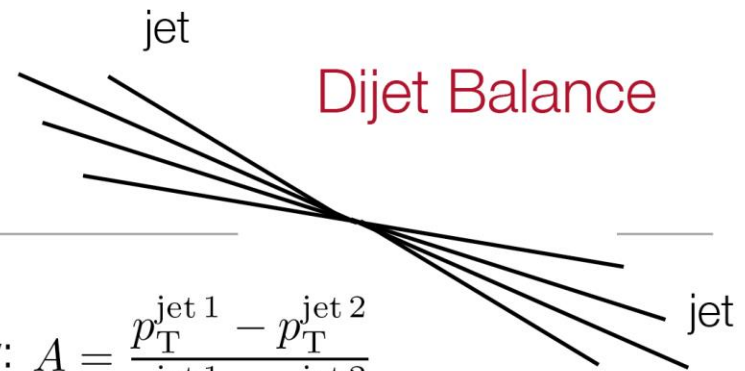
Jet energy calibration

Simple Photon+jet balance
Bias due to soft veto on second jet

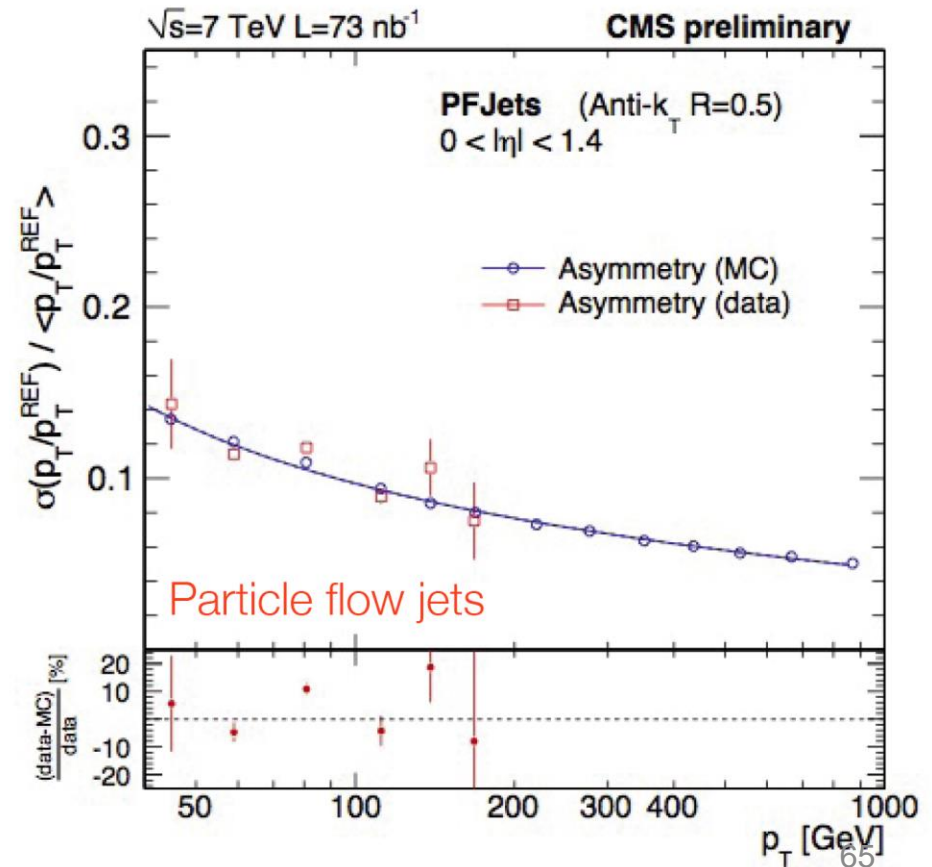
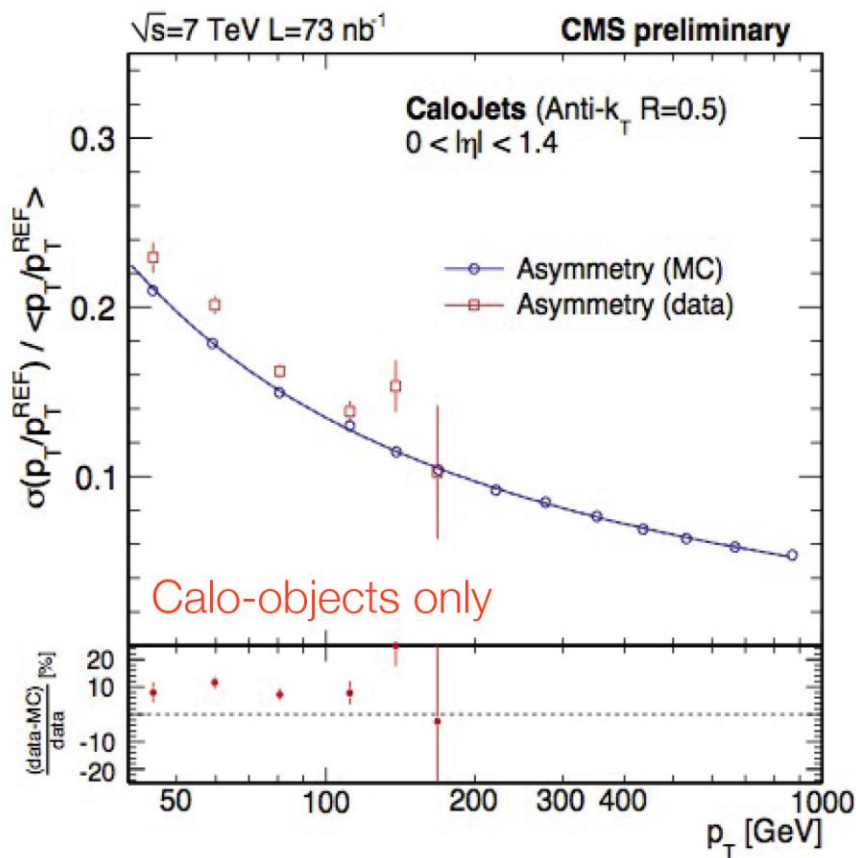
MET projection fraction method
Sums over non-photon E_T for balance



Jet energy resolution



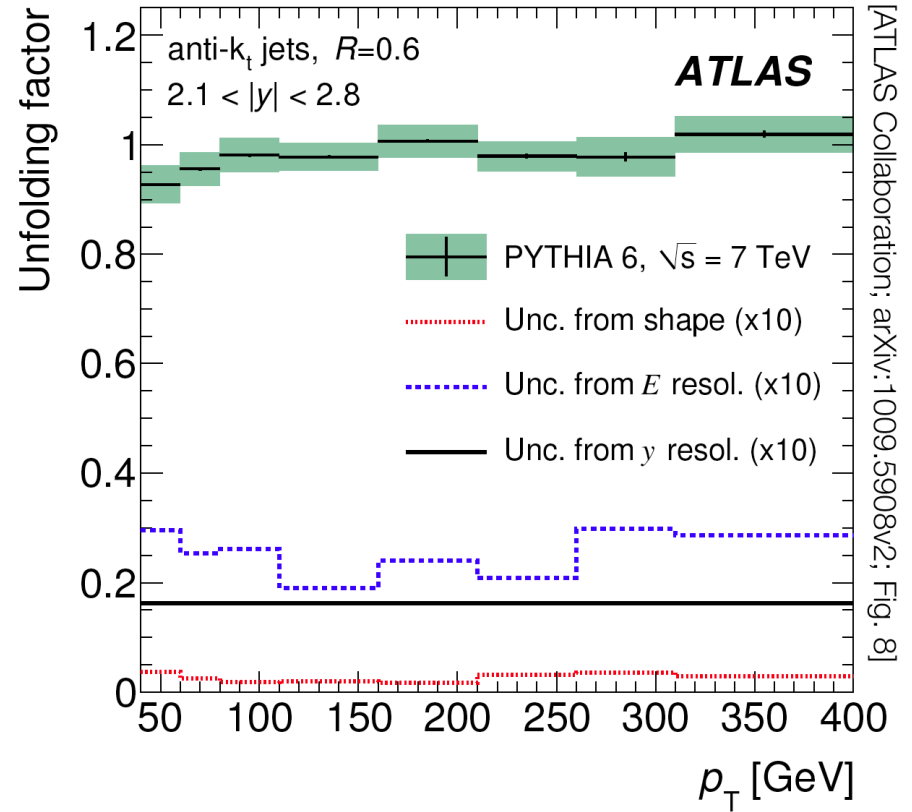
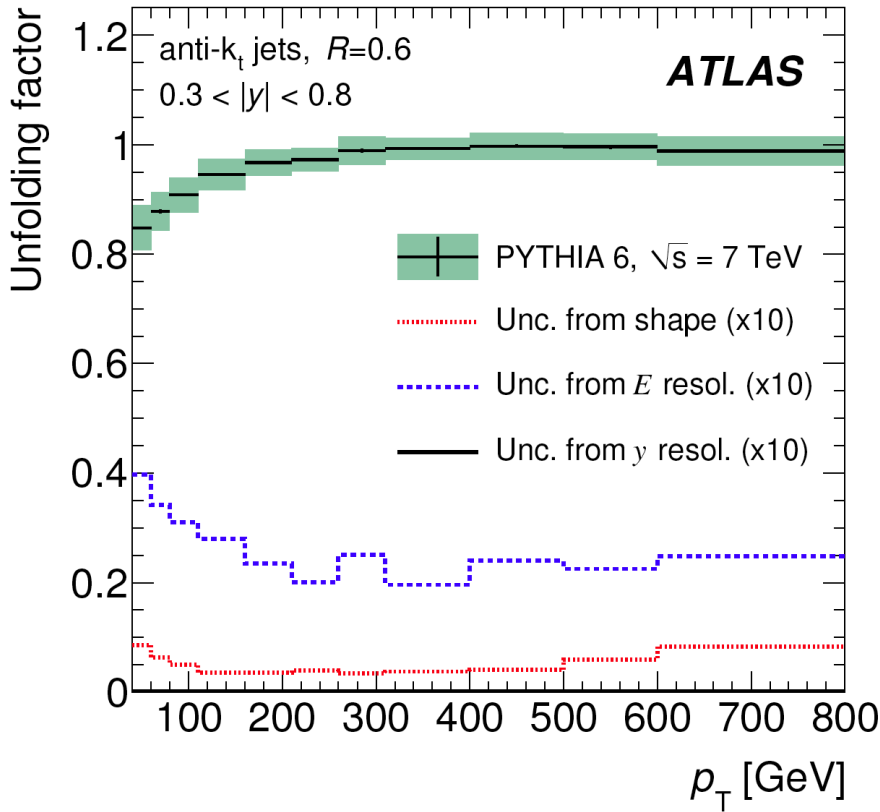
Resolution: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$ using p_T asymmetry: $A = \frac{p_T^{\text{jet } 1} - p_T^{\text{jet } 2}}{p_T^{\text{jet } 1} + p_T^{\text{jet } 2}}$



Resolution unfolding

Measured spectrum =
Real spectrum \otimes Experim. resolution

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



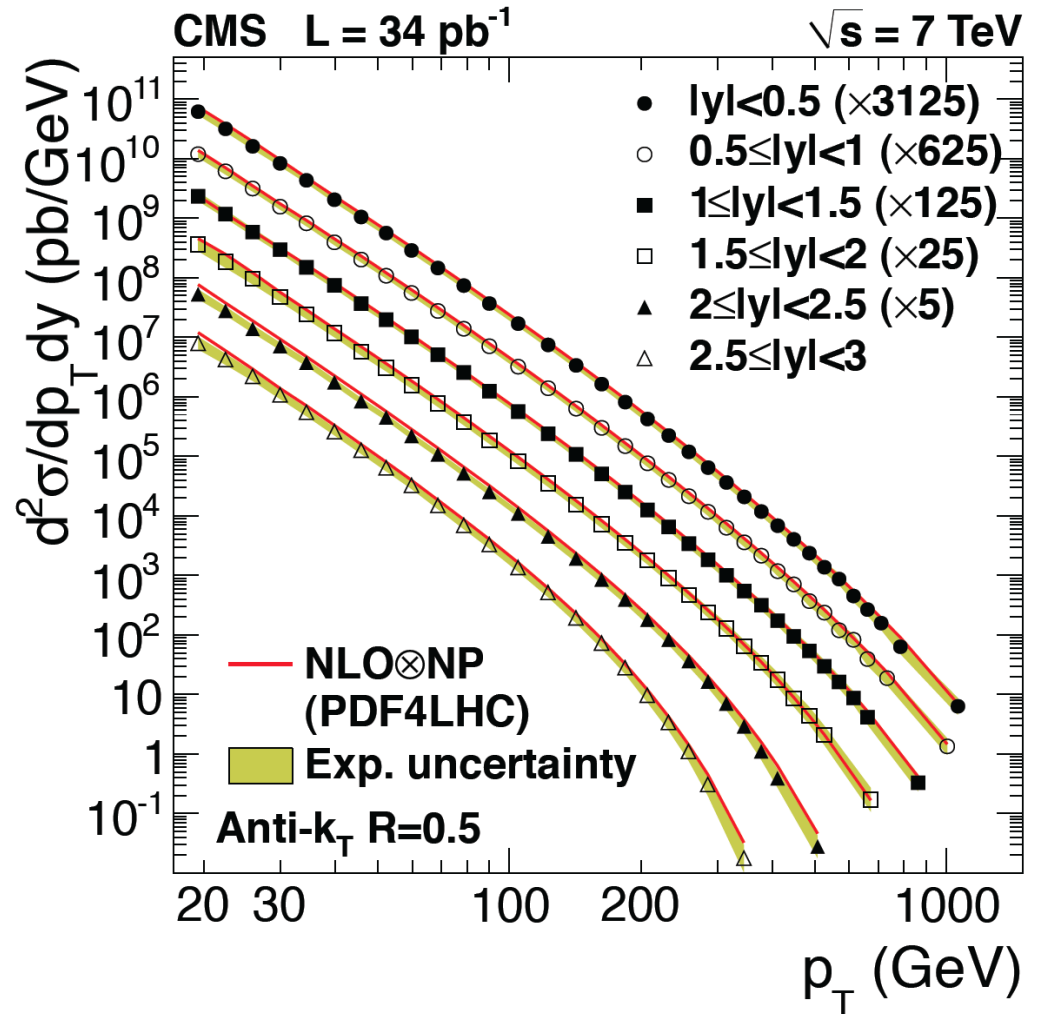
Inclusive jet cross-section

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%)



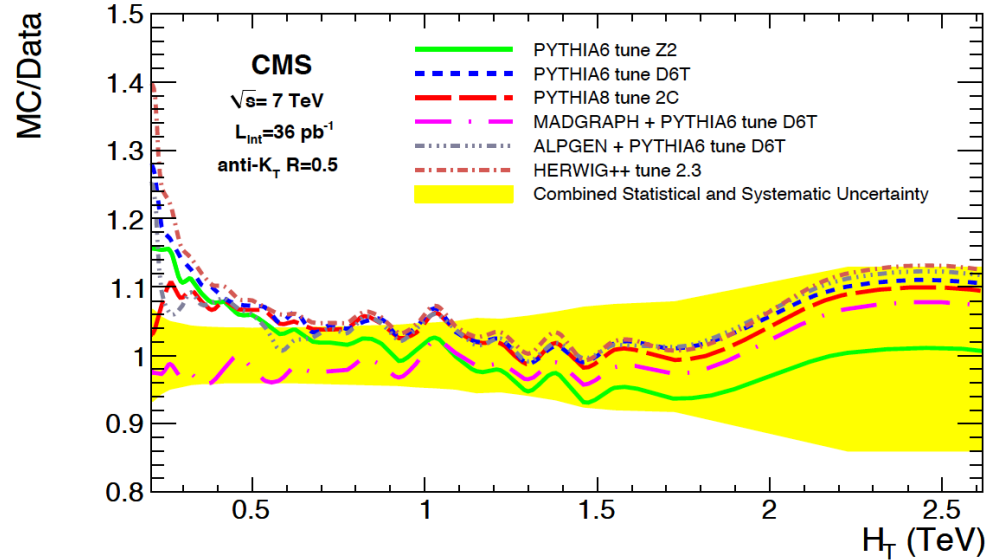
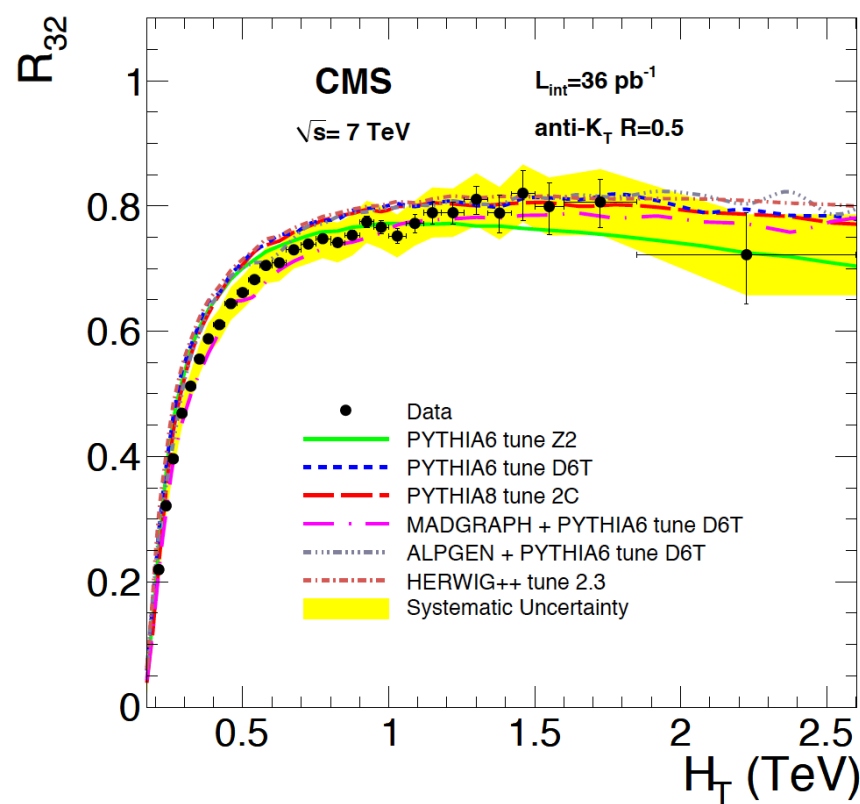
Inclusive jet cross-section

[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	<table border="1"> <thead> <tr> <th colspan="2">0 < y < 0.3</th> </tr> <tr> <th>p_T [GeV]</th> <th>60-80</th> </tr> </thead> <tbody> <tr> <td>Measured cross section [pb/GeV]</td> <td>3.5e+04</td> </tr> <tr> <td>NLO pQCD (CTEQ 6.6) × non-pert. corr. [pb/GeV]</td> <td>4.1e+04</td> </tr> <tr> <td>Non-perturbative correction</td> <td>0.92</td> </tr> <tr> <td>Statistical uncertainty</td> <td>0.011</td> </tr> <tr> <td>Absolute JES uncertainty</td> <td>+0.25 -0.22</td> </tr> <tr> <td>Unfolding uncertainty</td> <td>0.04</td> </tr> <tr> <td>Total systematic uncertainty</td> <td>+0.3 -0.2</td> </tr> <tr> <td>PDF uncertainty</td> <td>0.02</td> </tr> <tr> <td>Scale uncertainty</td> <td>+0.006 -0.04</td> </tr> <tr> <td>α_s uncertainty</td> <td>0.03</td> </tr> <tr> <td>Non-perturbative correction uncertainty</td> <td>+0.06 -0</td> </tr> <tr> <td>Total theory uncertainty</td> <td>+0.07 -0.05</td> </tr> </tbody> </table>										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
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Inclusive jet cross sections: 3-jet / 2-jet ratio

hep-ex 1106.0647, PLB 702 (2011) 336



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

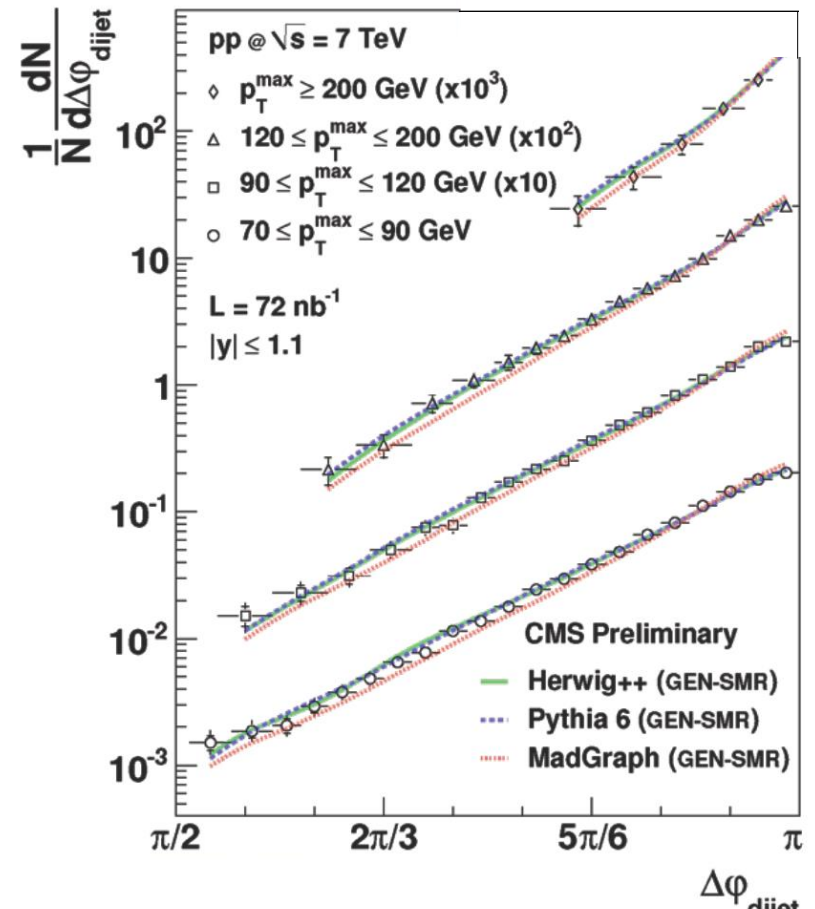
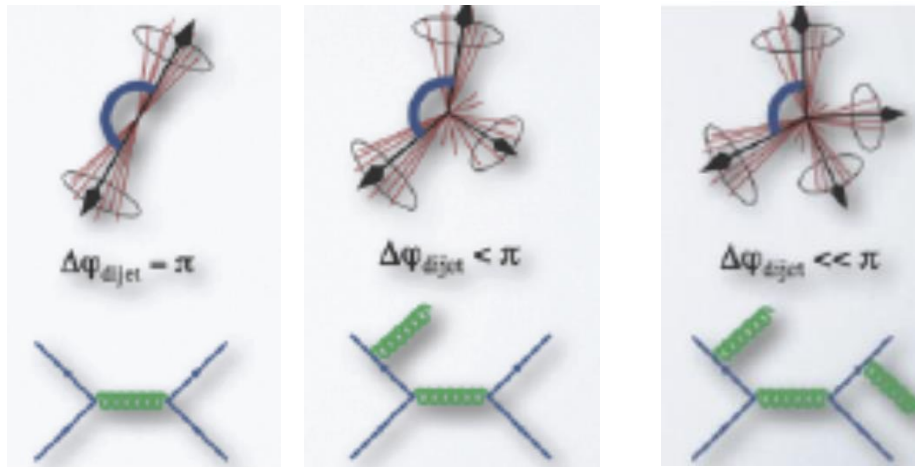
Jets: angular correlations

Difference in azimuth of the two leading jets

Probe of QCD high-order processes

Very slight dependence on JES

No dependence on luminosity



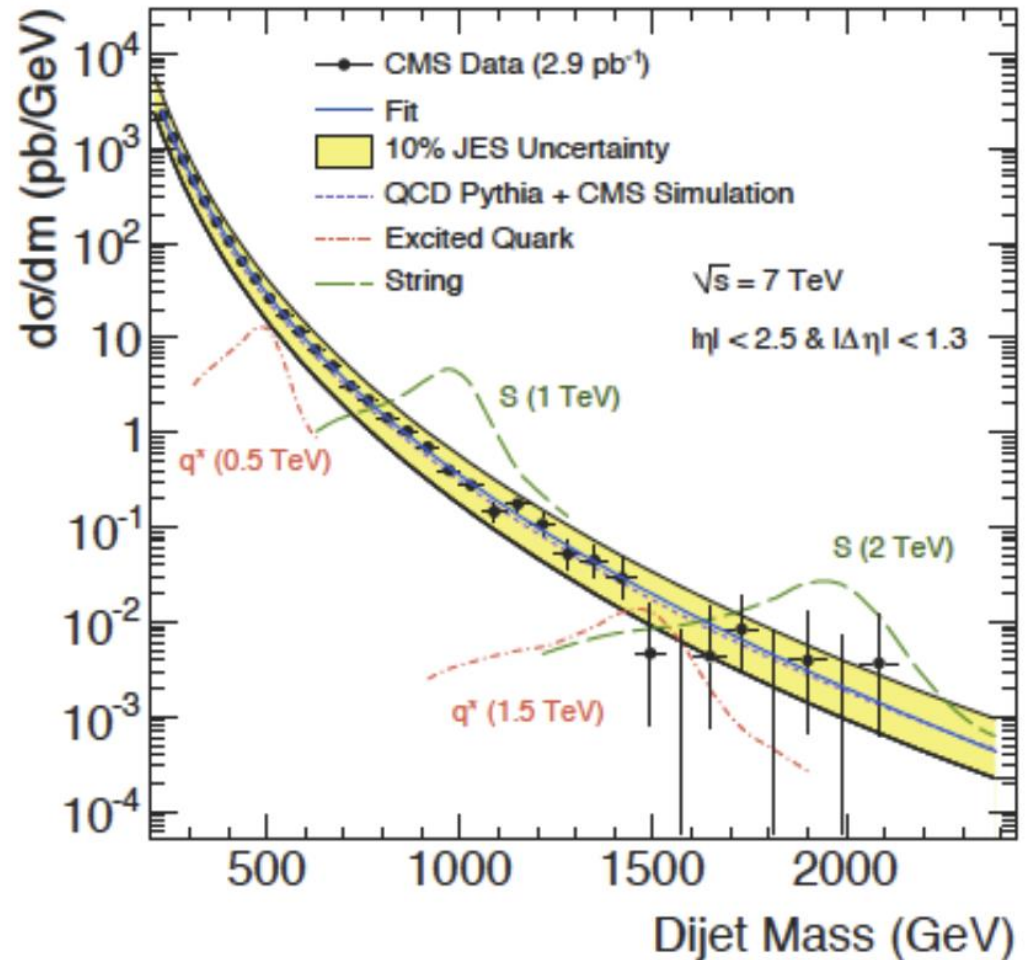
Dijet mass

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:

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

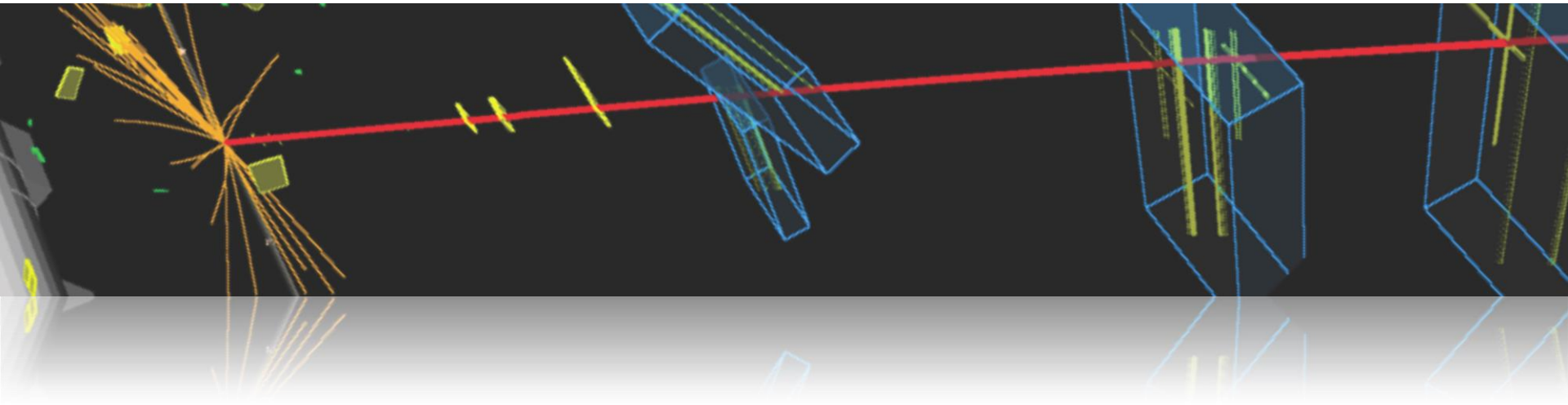
$$B = p_2 + p_3 \left(m/\sqrt{s}\right)$$



End of Lecture 2

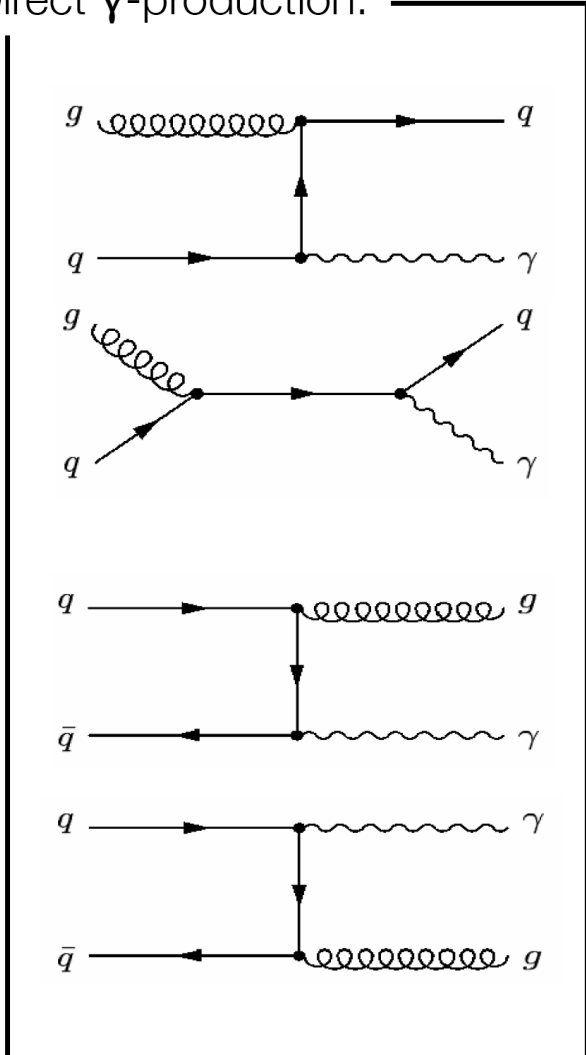
Additional material

W and Z bosons

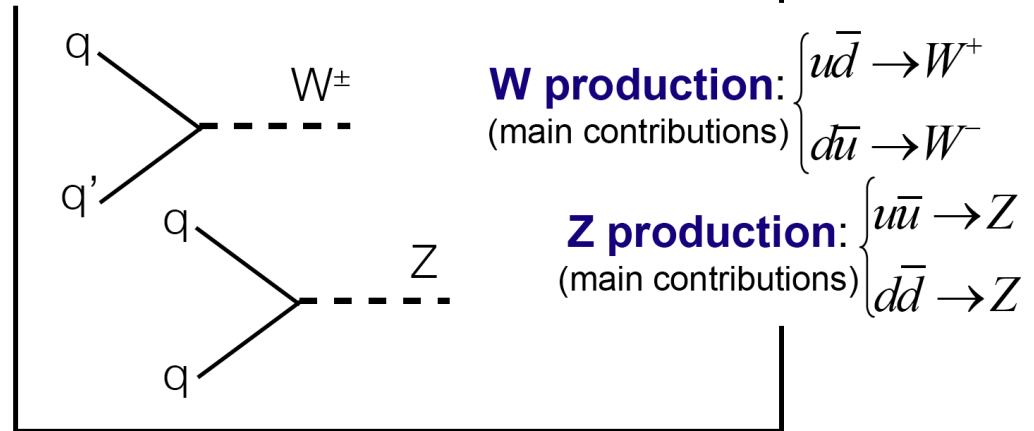


Vector boson production

Direct γ -production:



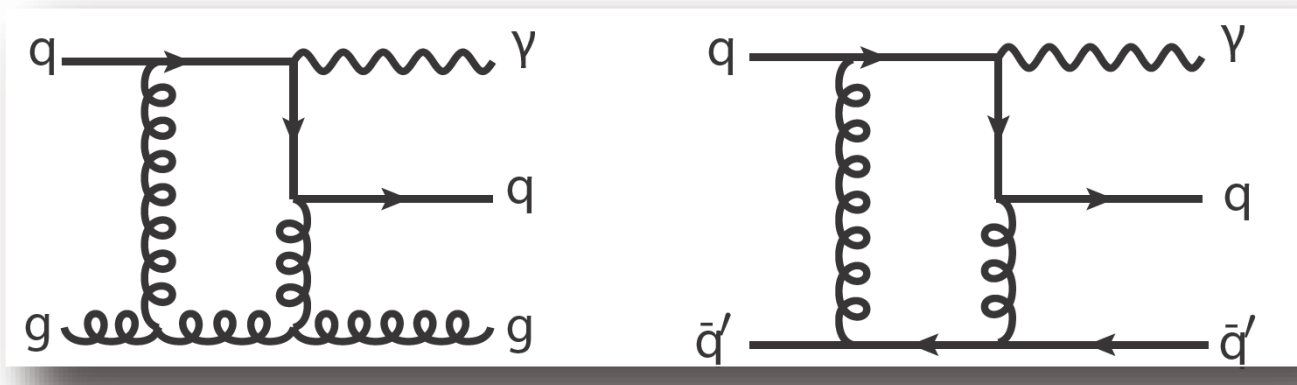
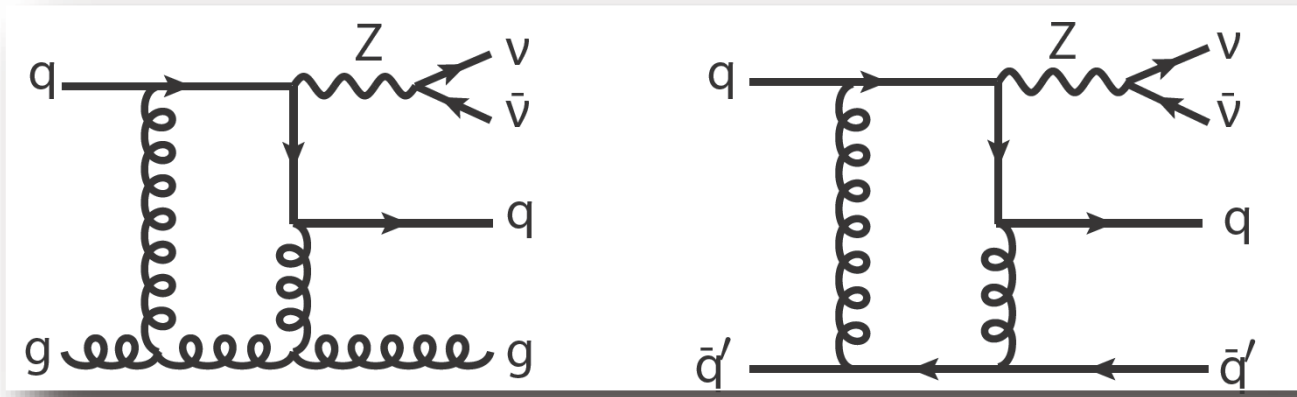
Singlet W/Z production:



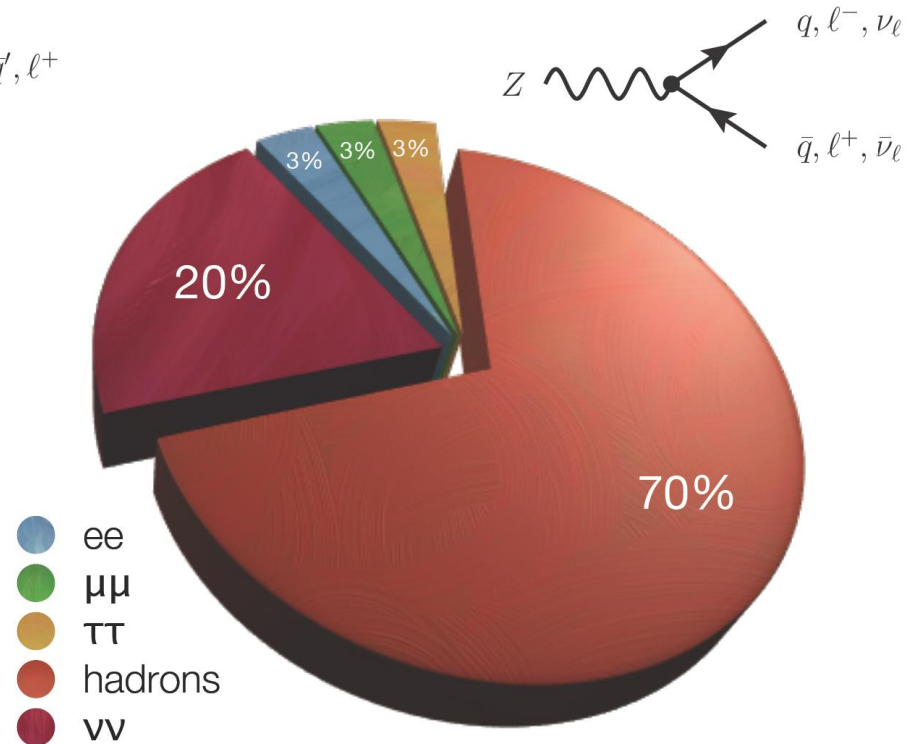
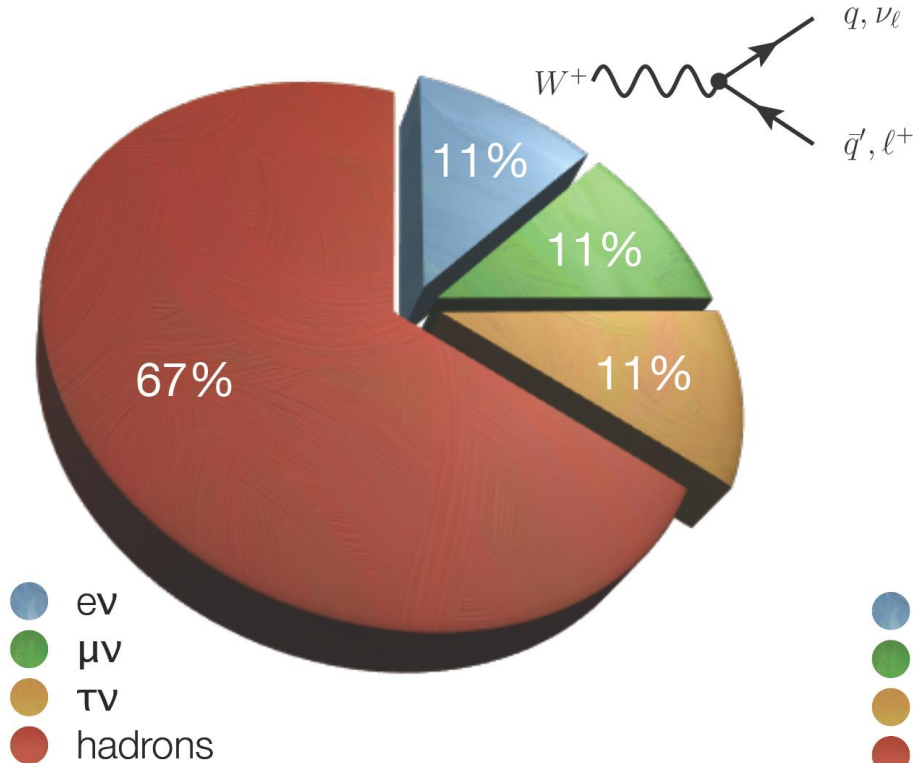
- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

➡ Constraints on sea and gluon distributions

Examples of high-order processes



W and Z boson decays



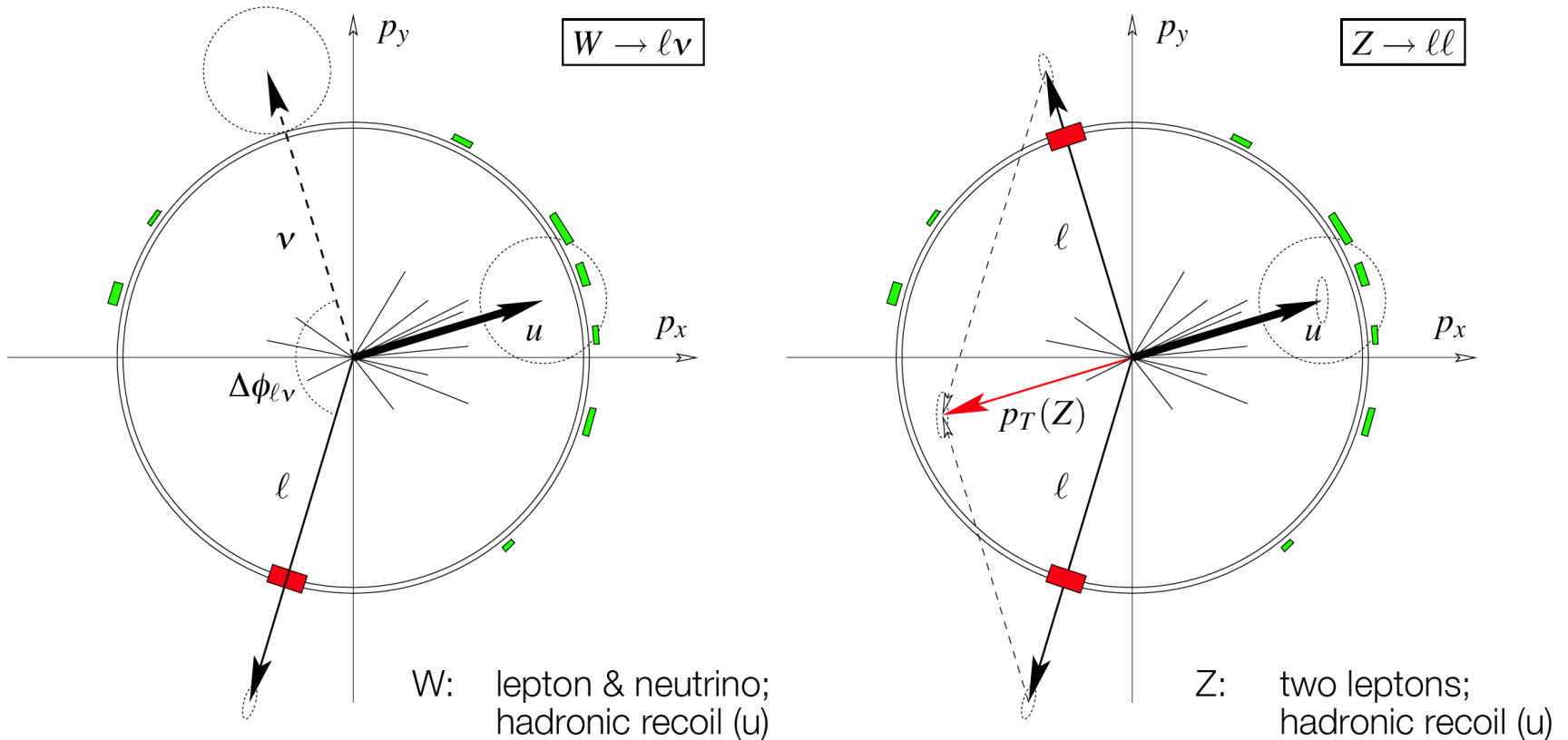
Leptonic decays (e/μ): very clean, but small(ish) branching fractions

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 \rightarrow 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 \rightarrow discriminate against QCD jets ...

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

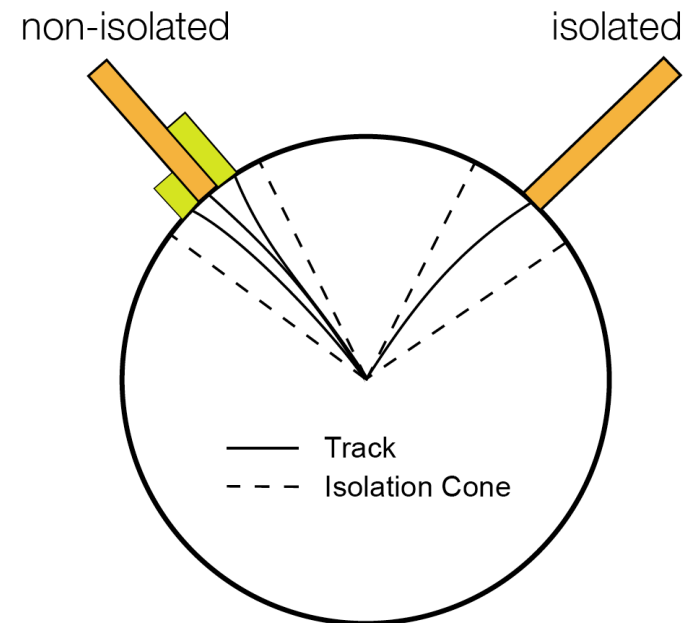
QCD jets may contain **real leptons**
e.g. from semileptonic B decays [$B \rightarrow l\nu_X$]

\rightarrow soft and surrounded by other particles

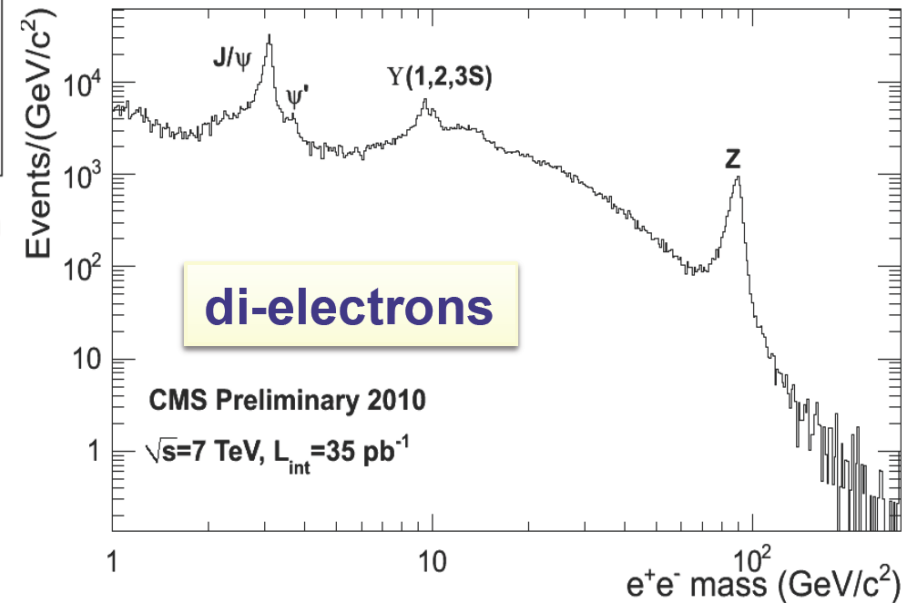
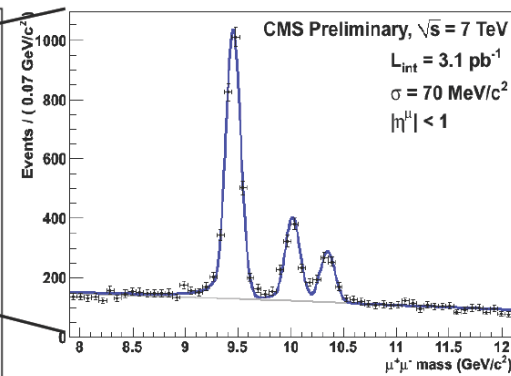
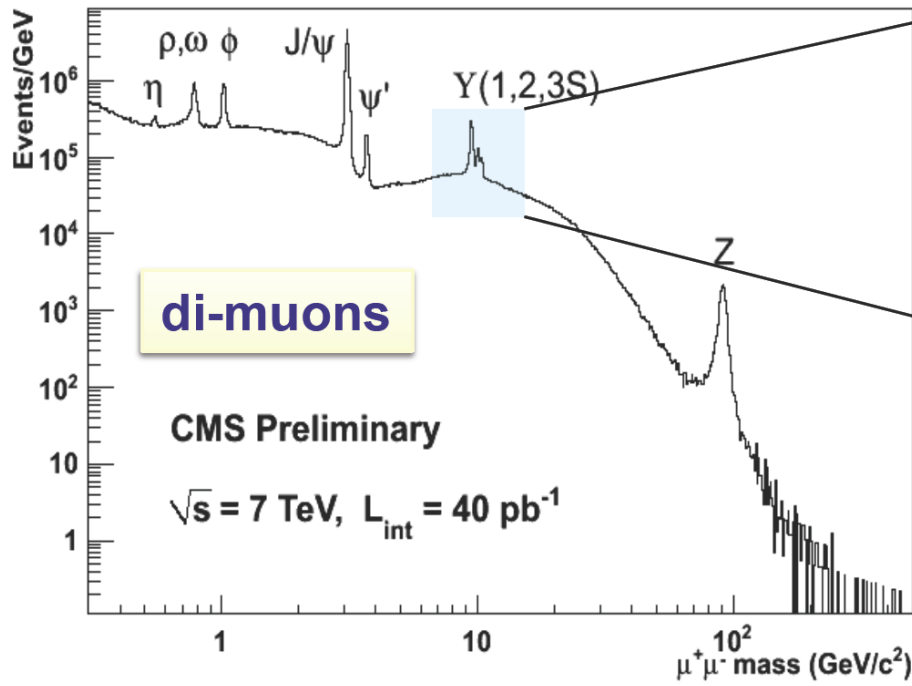
“Tight” lepton selection ...

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

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



Dilepton mass spectrum at 7 TeV



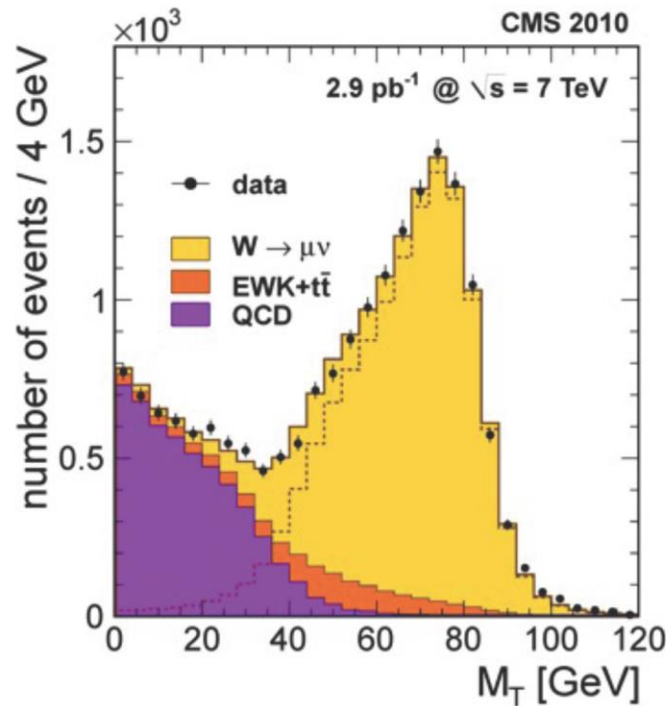
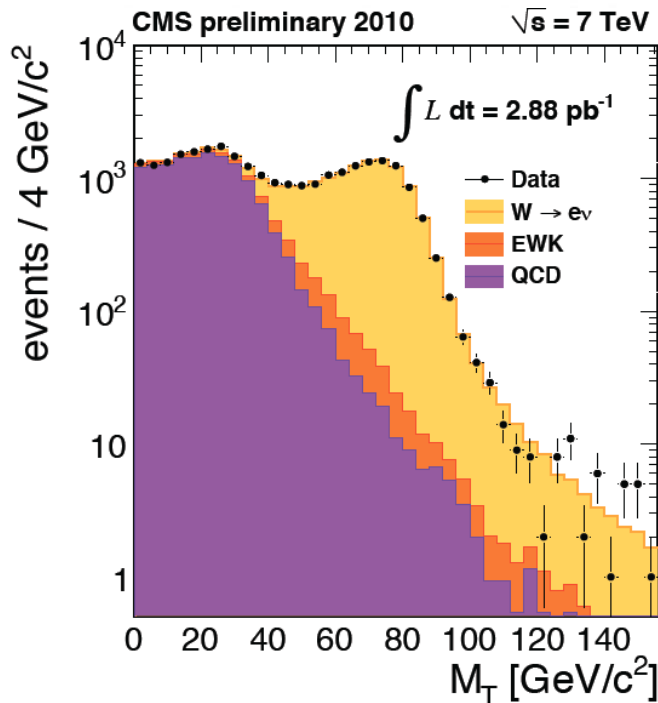
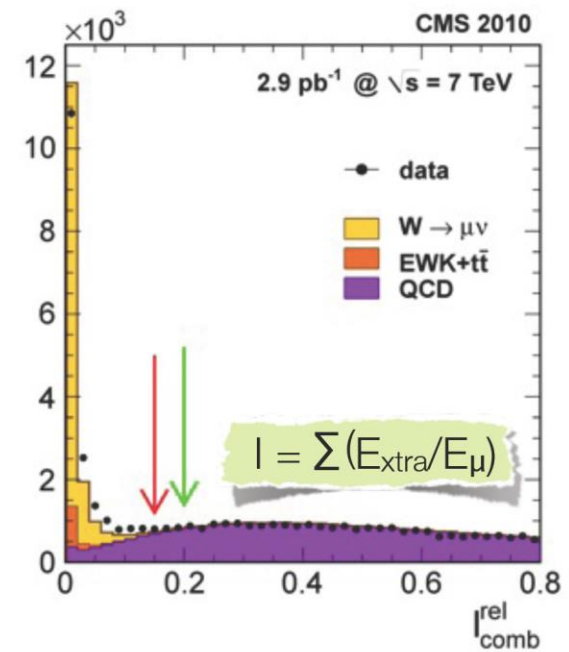
Example: CMS W Analysis

Select isolated electrons and muons ...

[muons: $p_T > 9$ GeV; electrons: $p_T > 20$ GeV]

Investigate transverse mass ...

[Use $E_{T,miss}$; $M_T = (p_{lep} + E_{T,miss})^{1/2}$]

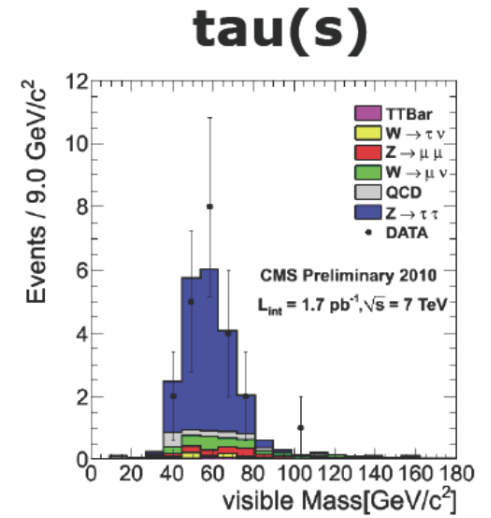
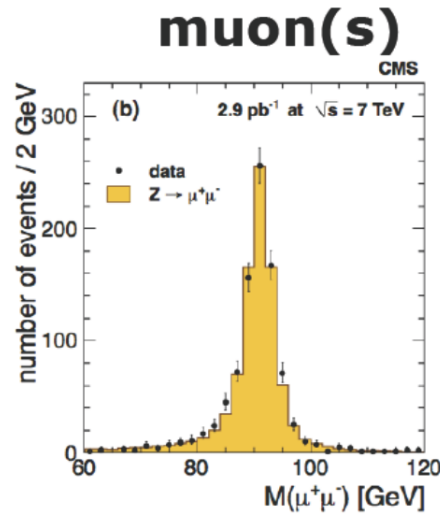
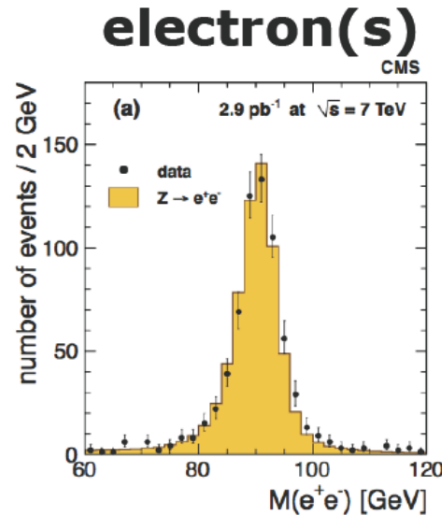


The W signal yield is extracted from a binned likelihood fit to the M_T distribution. Three different contributions:

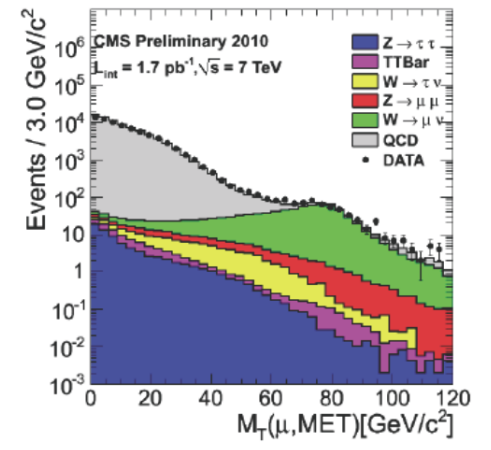
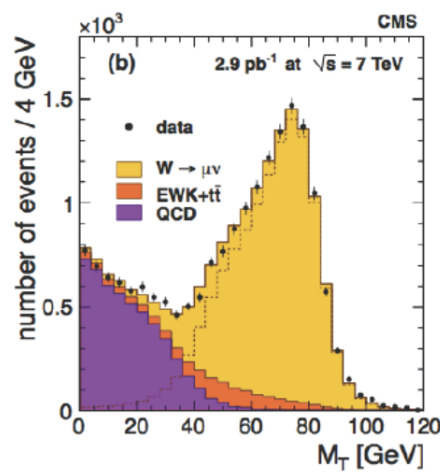
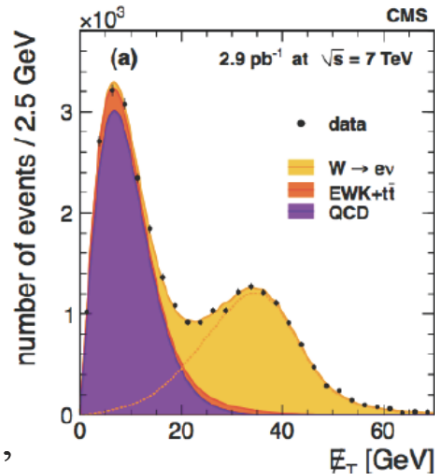
- W signal
- QCD background
- other (EWK) backgrounds.

W/Z production at 7 TeV

Z BOSON



W BOSON

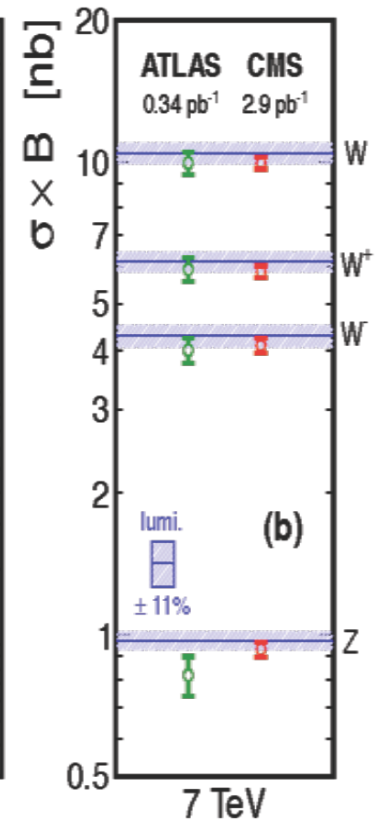
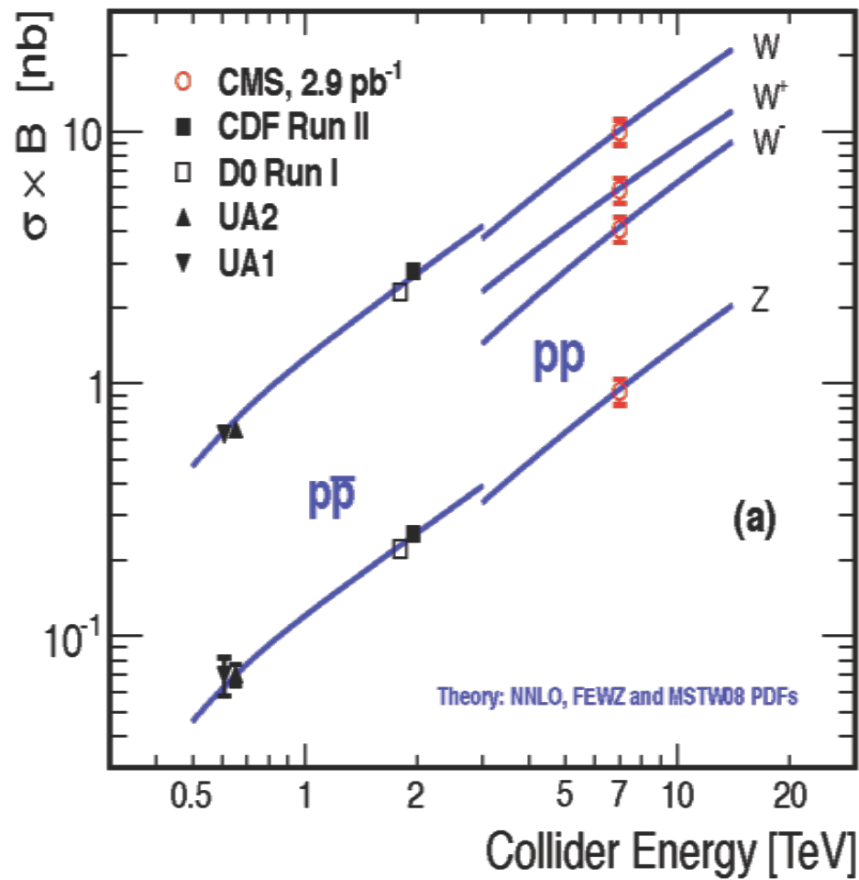
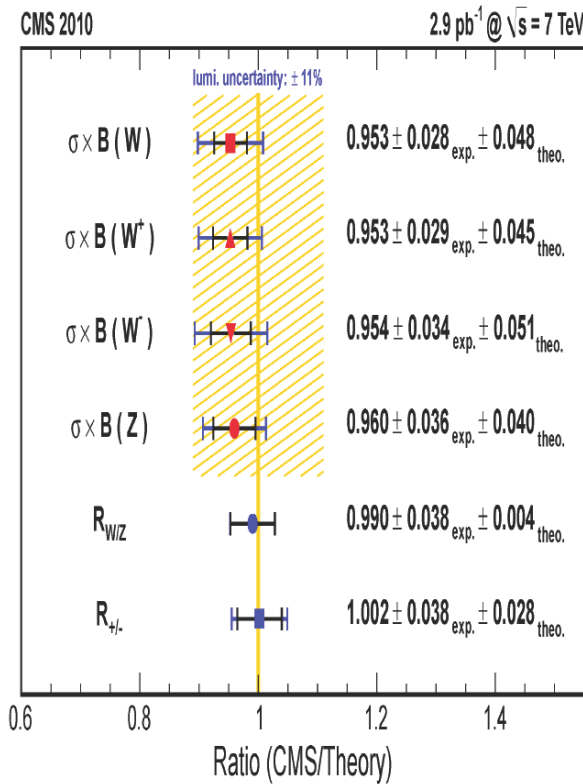


Transverse Mass,

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

W, Z cross-section v.s. \sqrt{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 $y=0$...

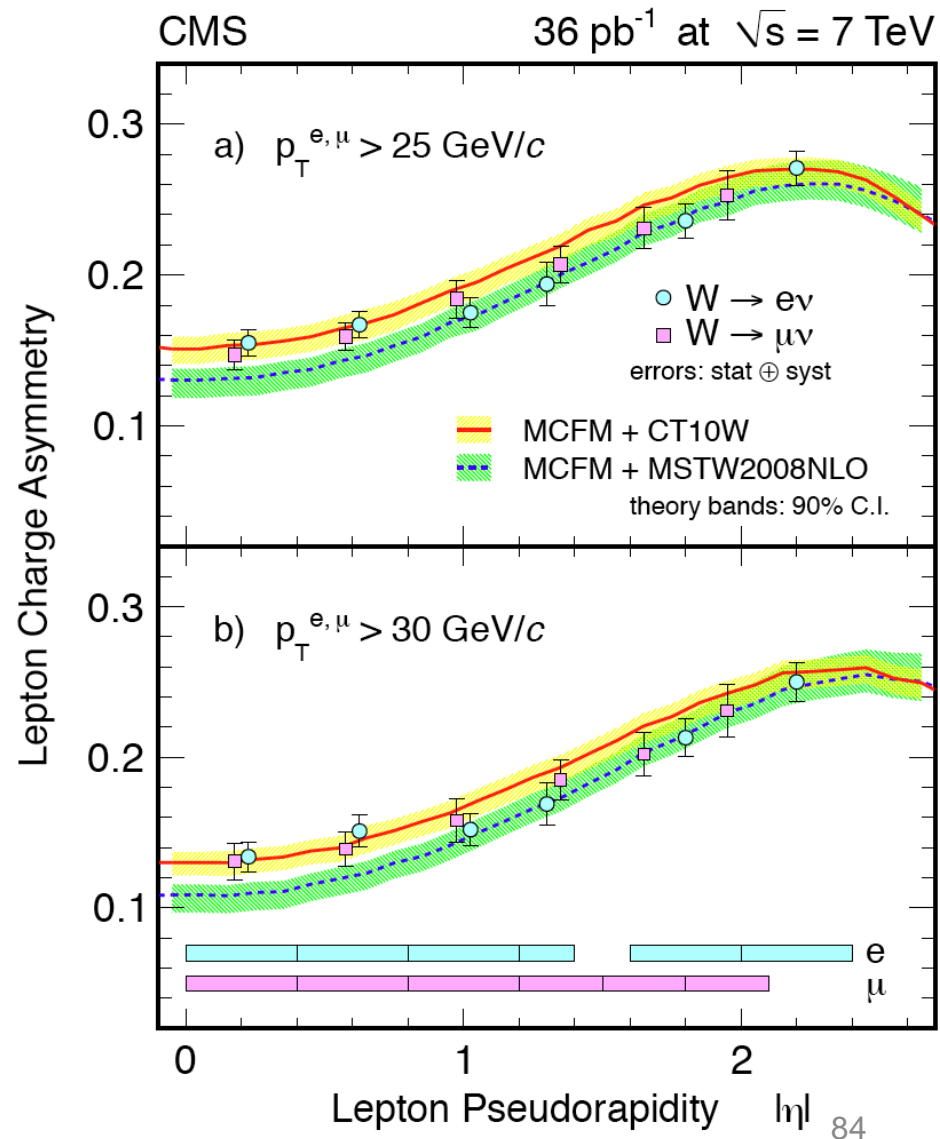
PDFs:

$u(x) > d(x)$ for large x ...

more W⁺ at positive rapidity

d/u ratio < 1 ...

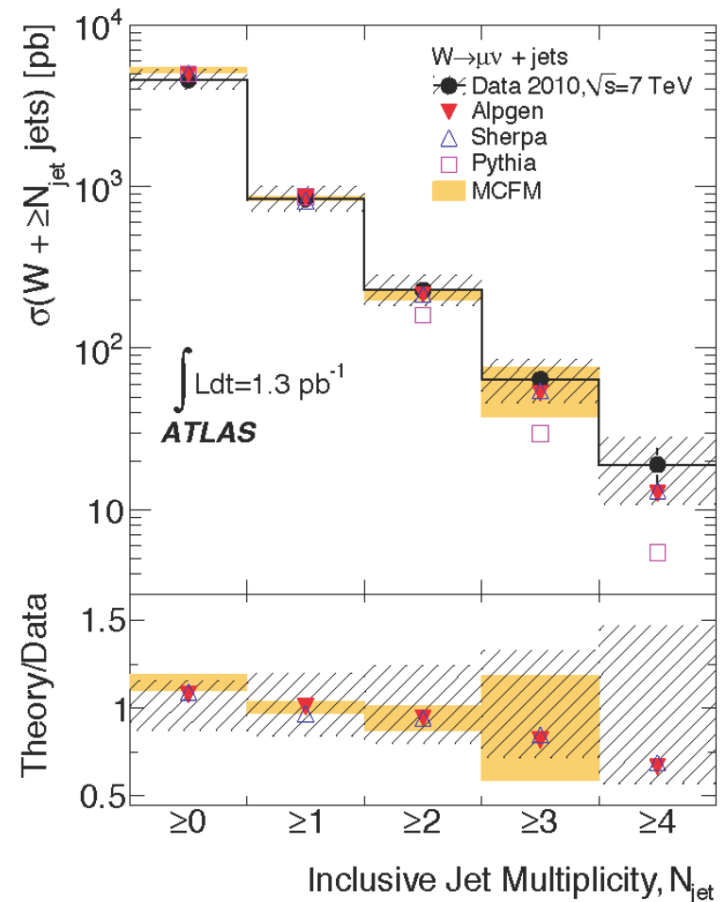
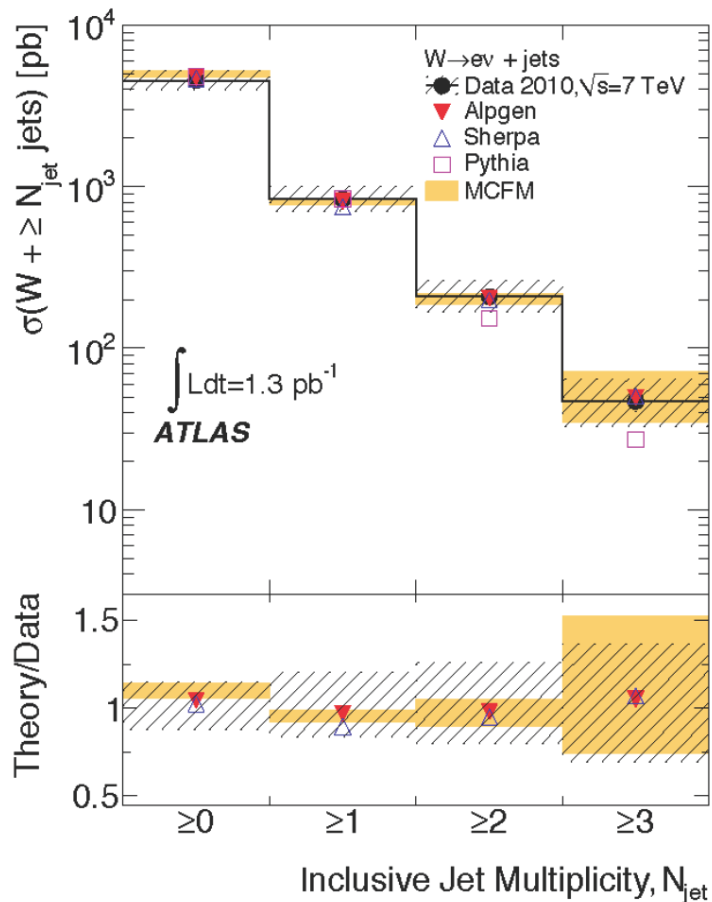
always more W⁺ than W⁻



W + Jets multiplicity

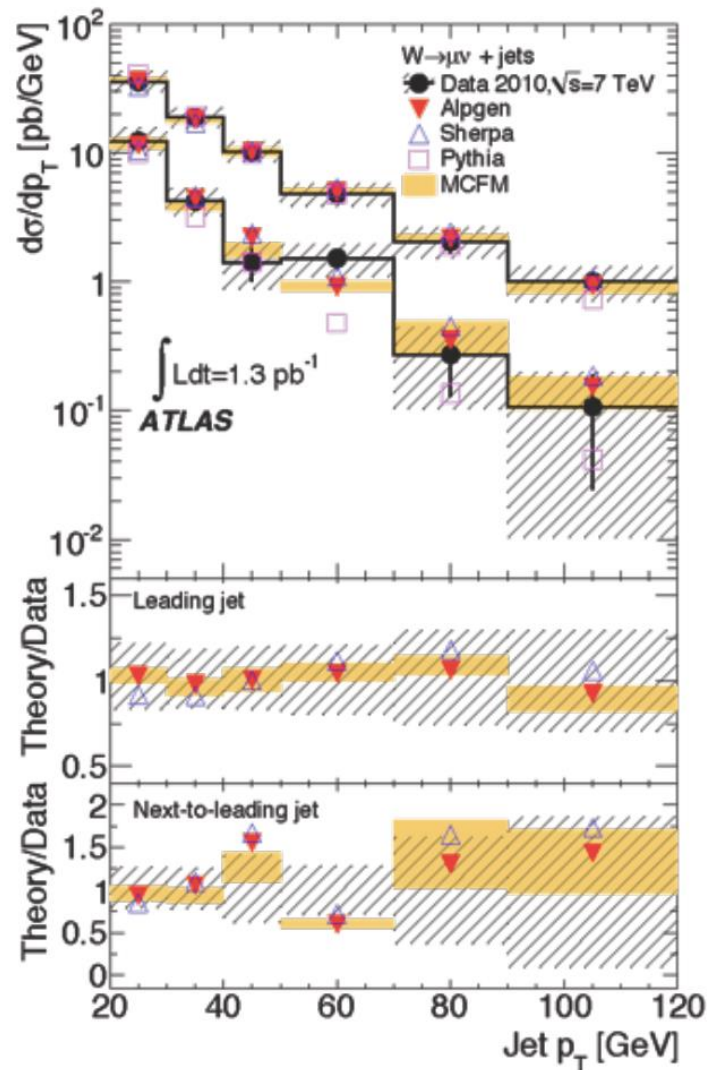
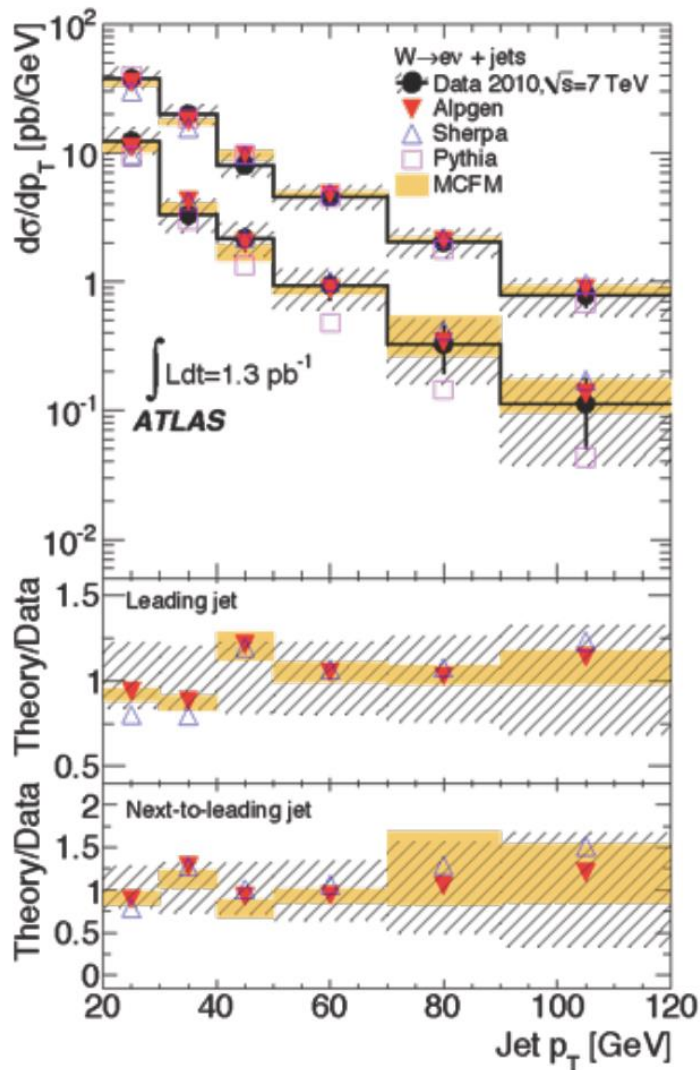
$|\eta| < 2.8$ and $p_T > 20$ GeV

arXiv:1012.5382

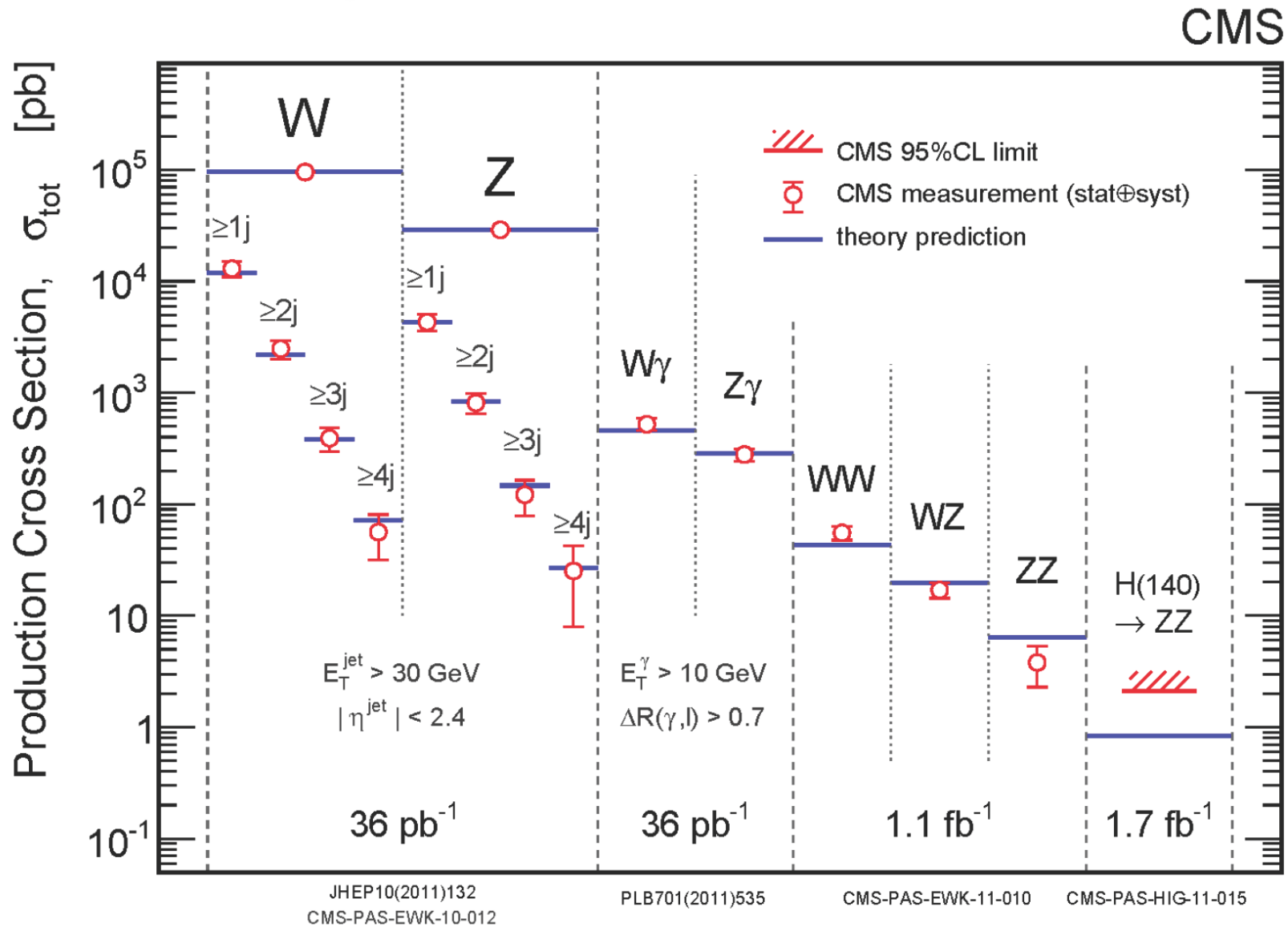


W + Jets P_T

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]

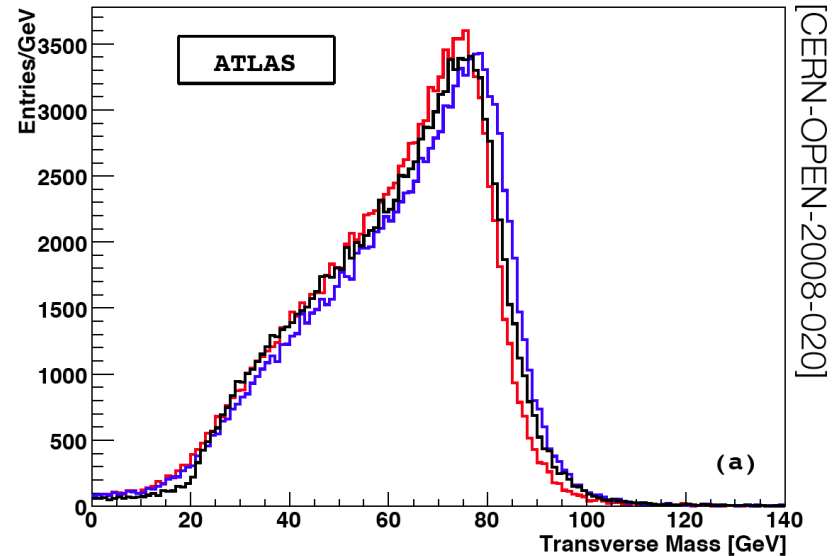
Lepton energy scale: 34 MeV

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

Hadronic recoil: 6 MeV

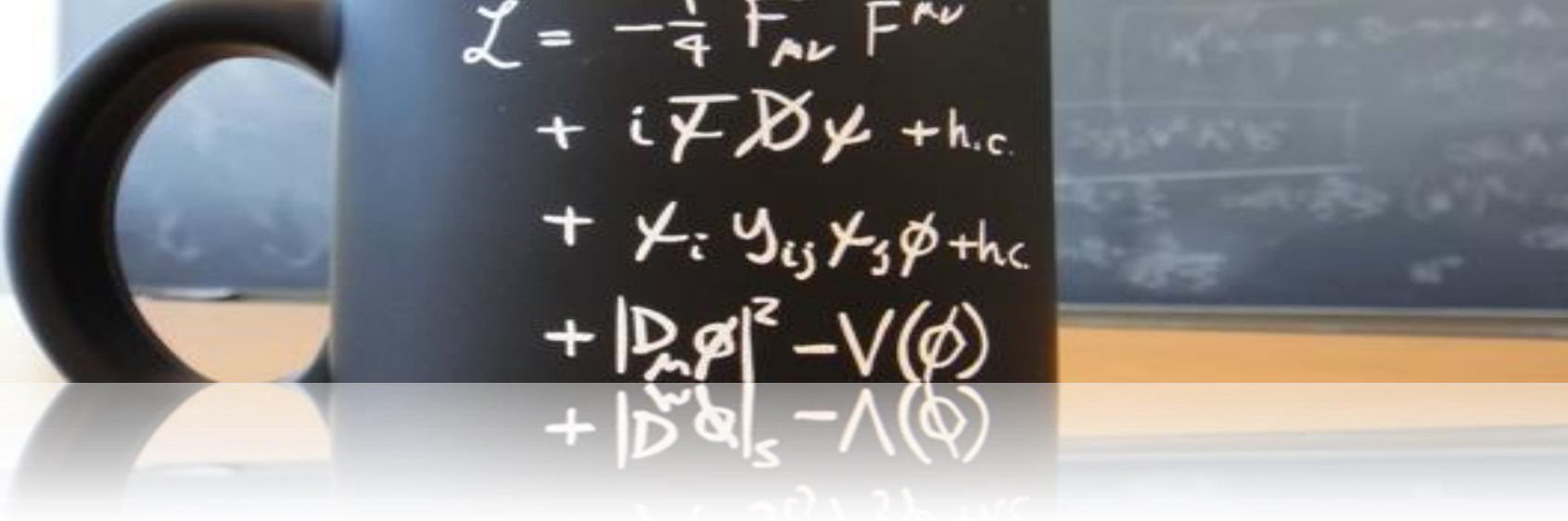
W production model [PDFs, ...]: 12 MeV

Templates for
 $m_W = 80.4 \pm 1.6$ GeV



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

Electroweak theory


$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi) \\ & + |D_\mu \chi|^2 - \Lambda(\chi)\end{aligned}$$

Cross section: using Feynman diagrams

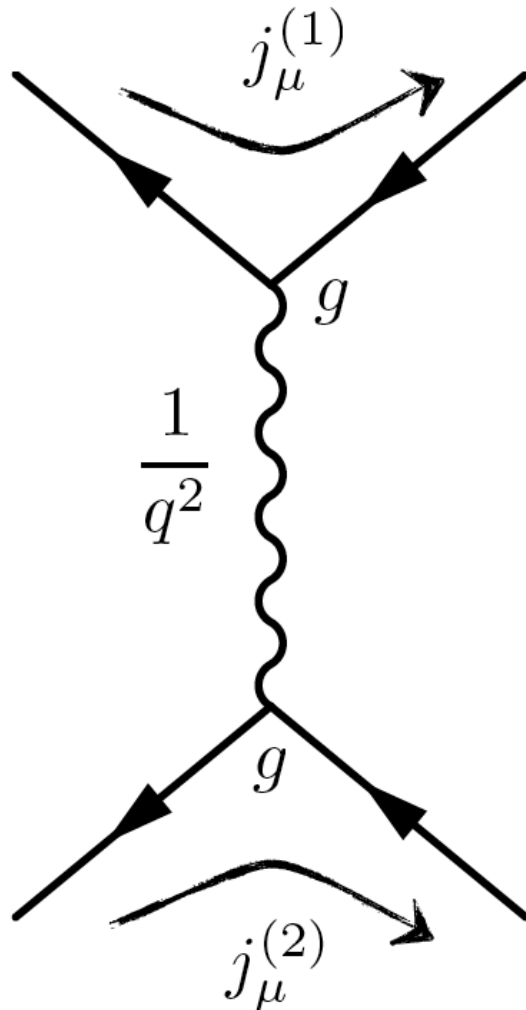
Fermi's Golden Rule

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

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 $|i\rangle \neq |f\rangle$]

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

Time Evolution

From Schrödinger-Equation
[Dirac picture]

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

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

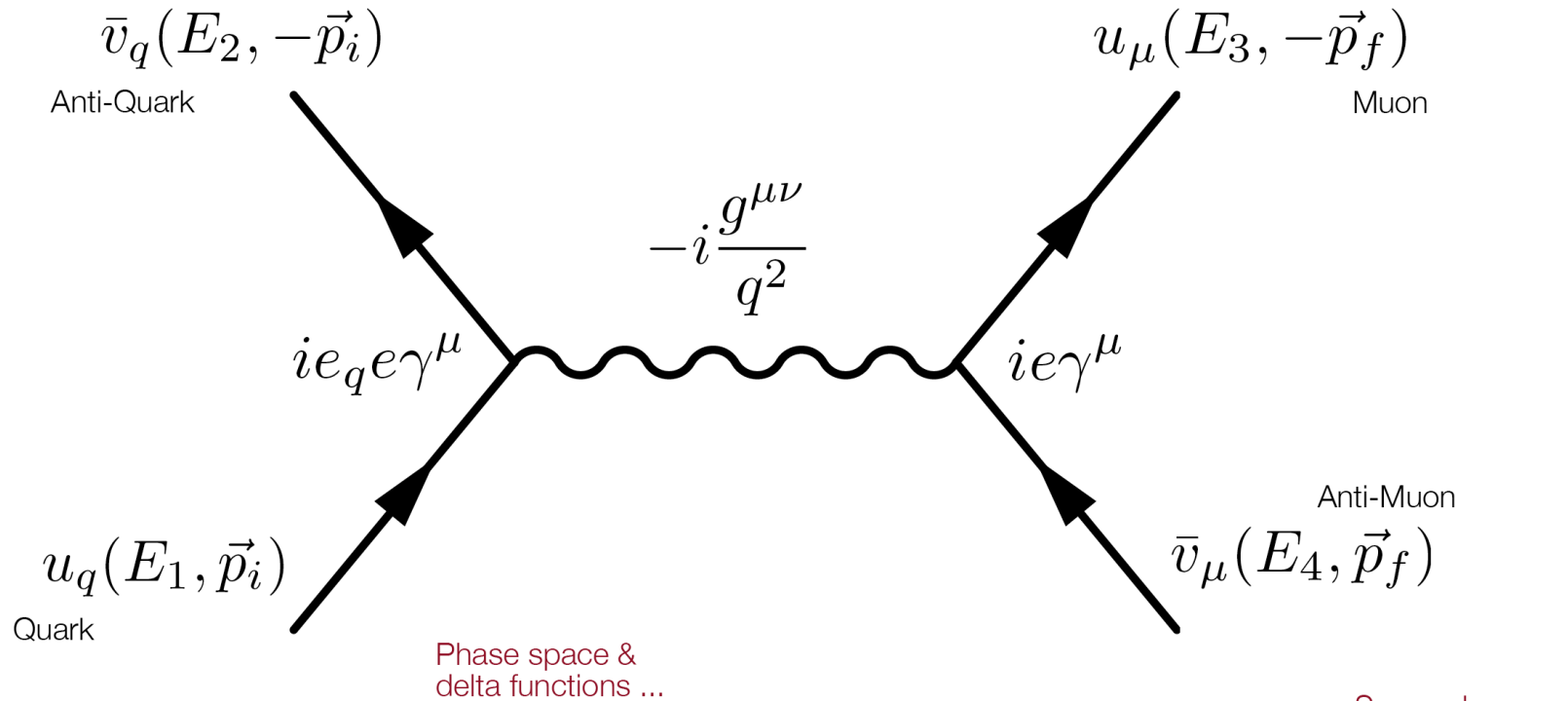
Lagrangian
of Interaction

Matrix element

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

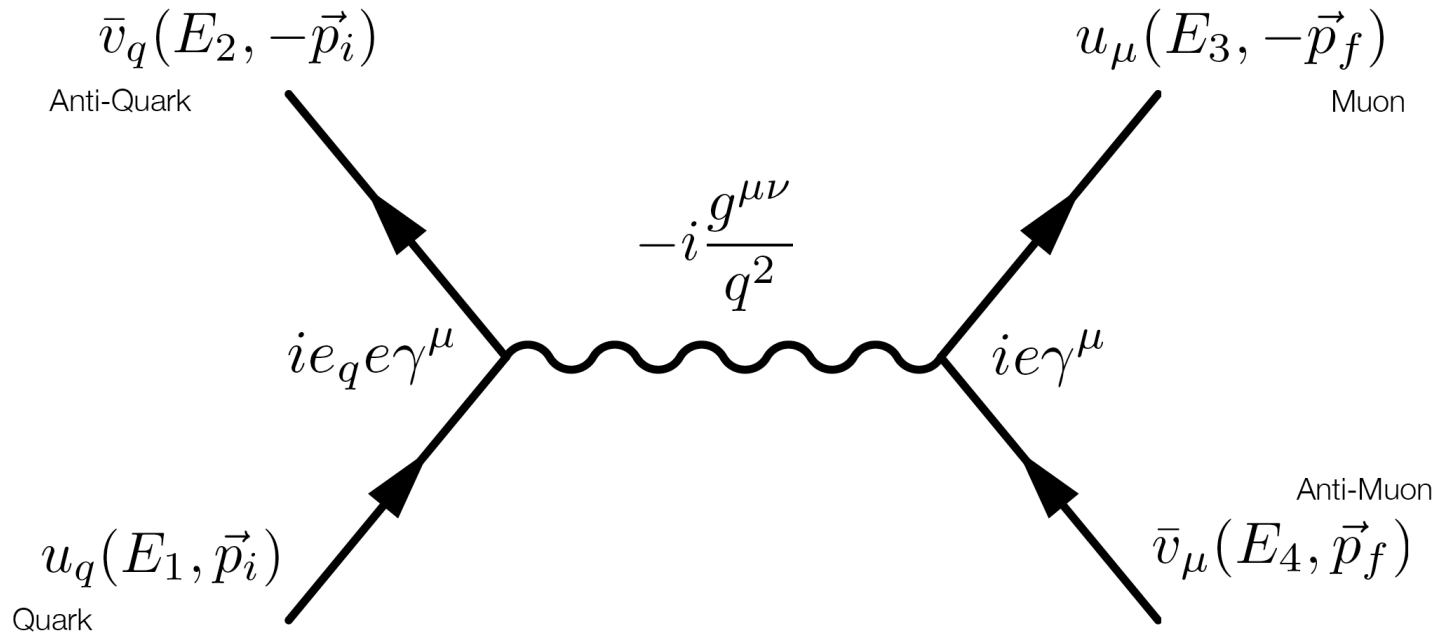
→ Feynman rules

Example: Drell-Yan Process



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

Example: Drell-Yan Process

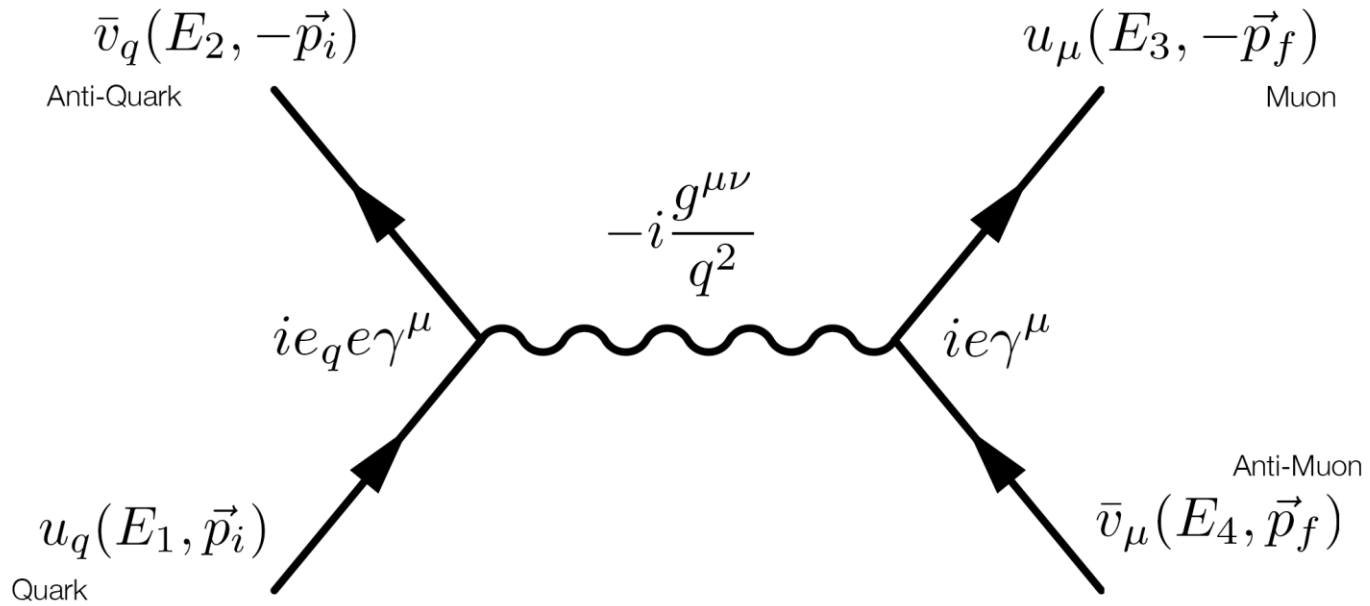


Averaging over initial spins

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



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

Labels for the equation components:

- $e_q e^2$: Couplings
- \bar{v}_q : Anti-Quark
- u_q : Quark
- \bar{v}_μ : Anti-Muon
- u_μ : Muon
- q^2 : Propagator

Example: Drell-Yan Process

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



$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{e^4}{32\pi^2} e_q^2 \cdot \frac{1}{s} \cdot \frac{t^2 + u^2}{s^2} \\ &= \frac{e^4}{64\pi^2} e_q^2 \cdot \frac{1}{s} \cdot (1 + \cos^2 \theta) \end{aligned}$$

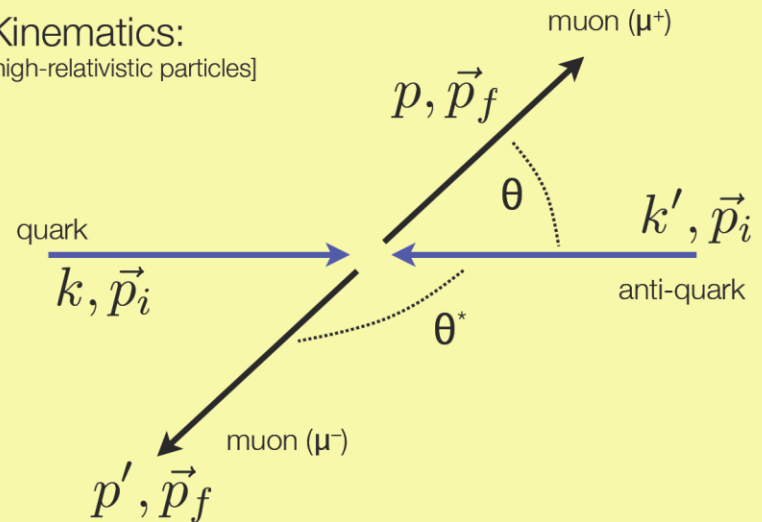


with $e^2 = 4\pi\alpha$

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

[θ in CMS frame]

Kinematics:
[high-relativistic particles]



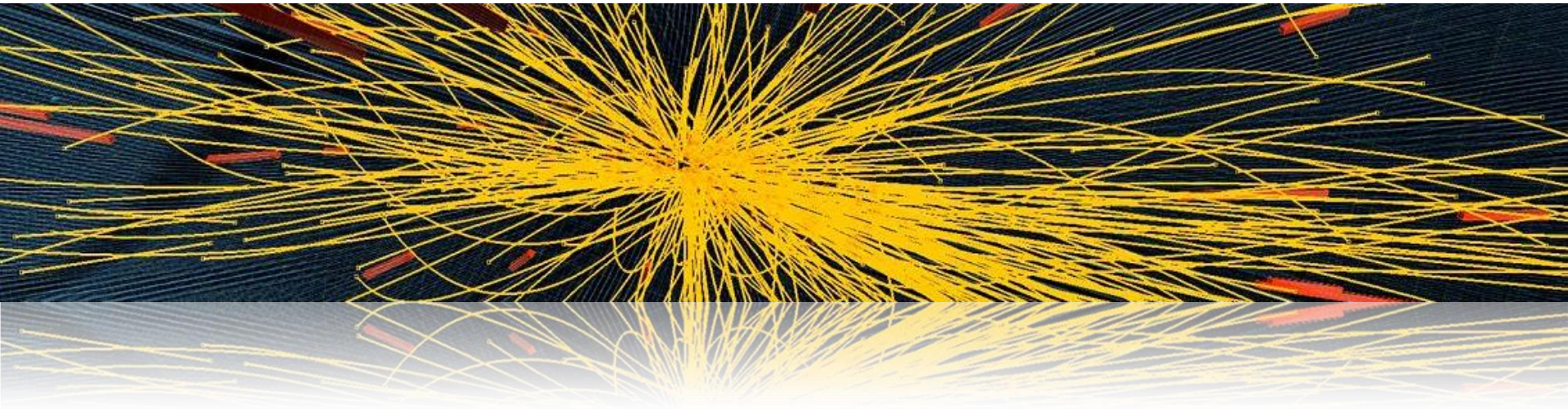
Mandelstam
variables

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

$$\begin{aligned} t = (k - p)^2 &\approx -2kp \approx -2E_i^2(1 - \cos \theta^*) \\ &\approx -\frac{s}{2}(1 + \cos \theta) \end{aligned}$$

$$\begin{aligned} u = (k - p')^2 &\approx -2kp' \approx -2E_i^2(1 - \cos \theta) \\ &\approx -\frac{s}{2}(1 - \cos \theta) \end{aligned}$$

Hadron Interactions



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:

$$E^* = \gamma_f \cdot E - \gamma_f \beta_f \cdot p_{\parallel}$$

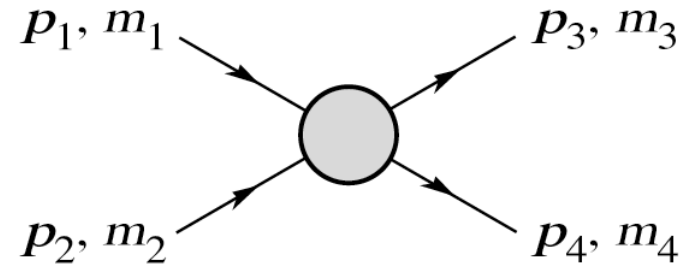
$$p_{\parallel}^* = \gamma_f \cdot p_{\parallel} - \gamma_f \beta_f \cdot E$$

$$p_T^* = p_T$$

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

Mandelstam variables

Feynman diagrams

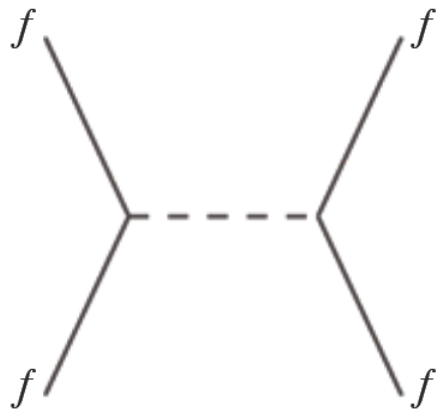


$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

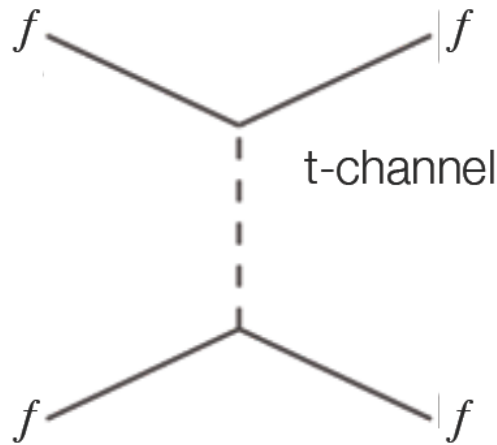
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

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

s-channel

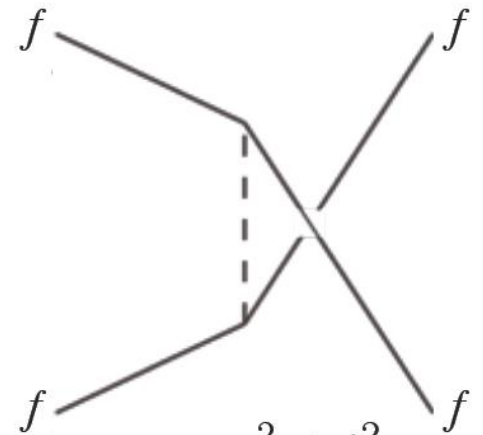


$$\sigma \propto \frac{t^2 + u^2}{s^2}$$



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

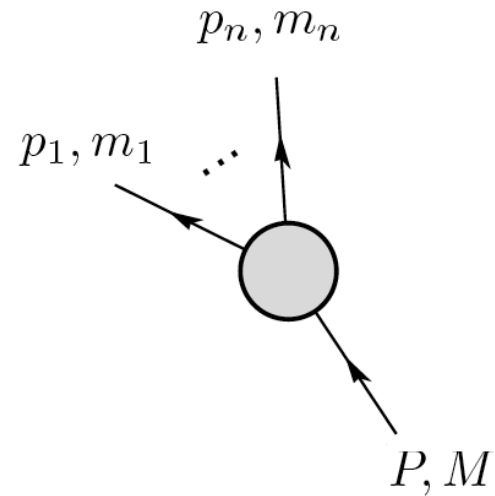
u-channel



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

Particle decays

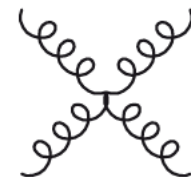
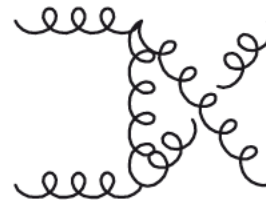
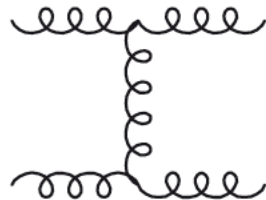
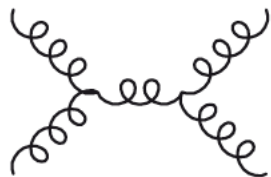
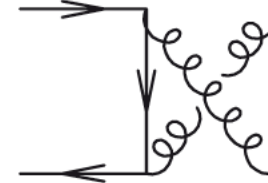
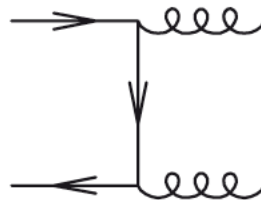
Partial
Decay Rate:



$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 \\ \times d\Phi_n (P; p_1, \dots, p_n)$$

Hard processes with quarks and gluons

Examples:



Q² evolution equations

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

$$\frac{\partial}{\partial \log Q^2} \begin{bmatrix} q(x, Q^2) \\ g(x, Q^2) \end{bmatrix} = \frac{\alpha_s}{2\pi} \begin{bmatrix} \mathcal{P}_{q/q} & \mathcal{P}_{g/q} \\ \mathcal{P}_{g/q} & \mathcal{P}_{g/g} \end{bmatrix} \otimes \begin{bmatrix} q(x, Q^2) \\ g(x, Q^2) \end{bmatrix}$$

PDFs

$$\mathcal{P} \otimes f(x, Q^2) = \int_x^1 \frac{dy}{y} \mathcal{P}(x/y) f(y, Q^2)$$

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

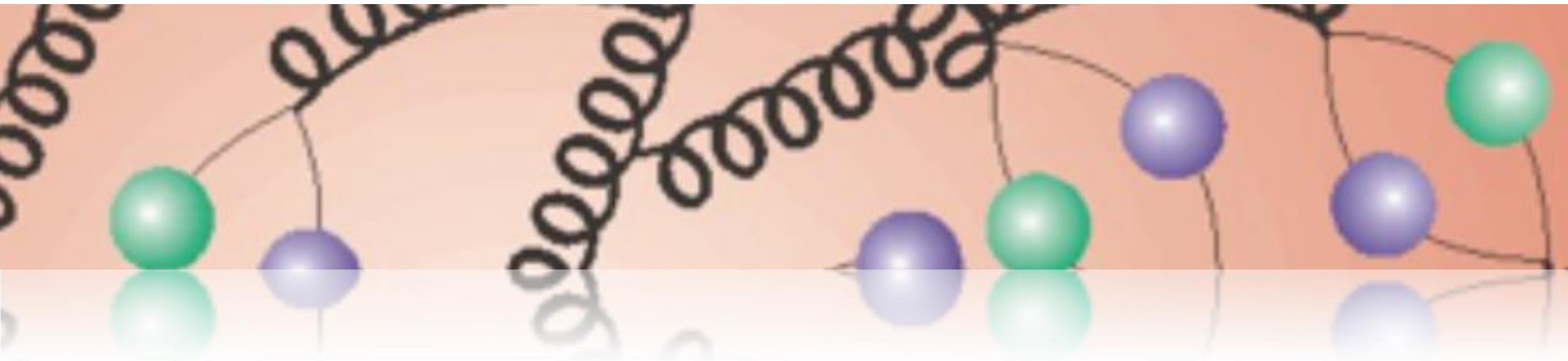
 $\frac{1}{2} [z^2 + (1-z^2)]$ (top right)

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

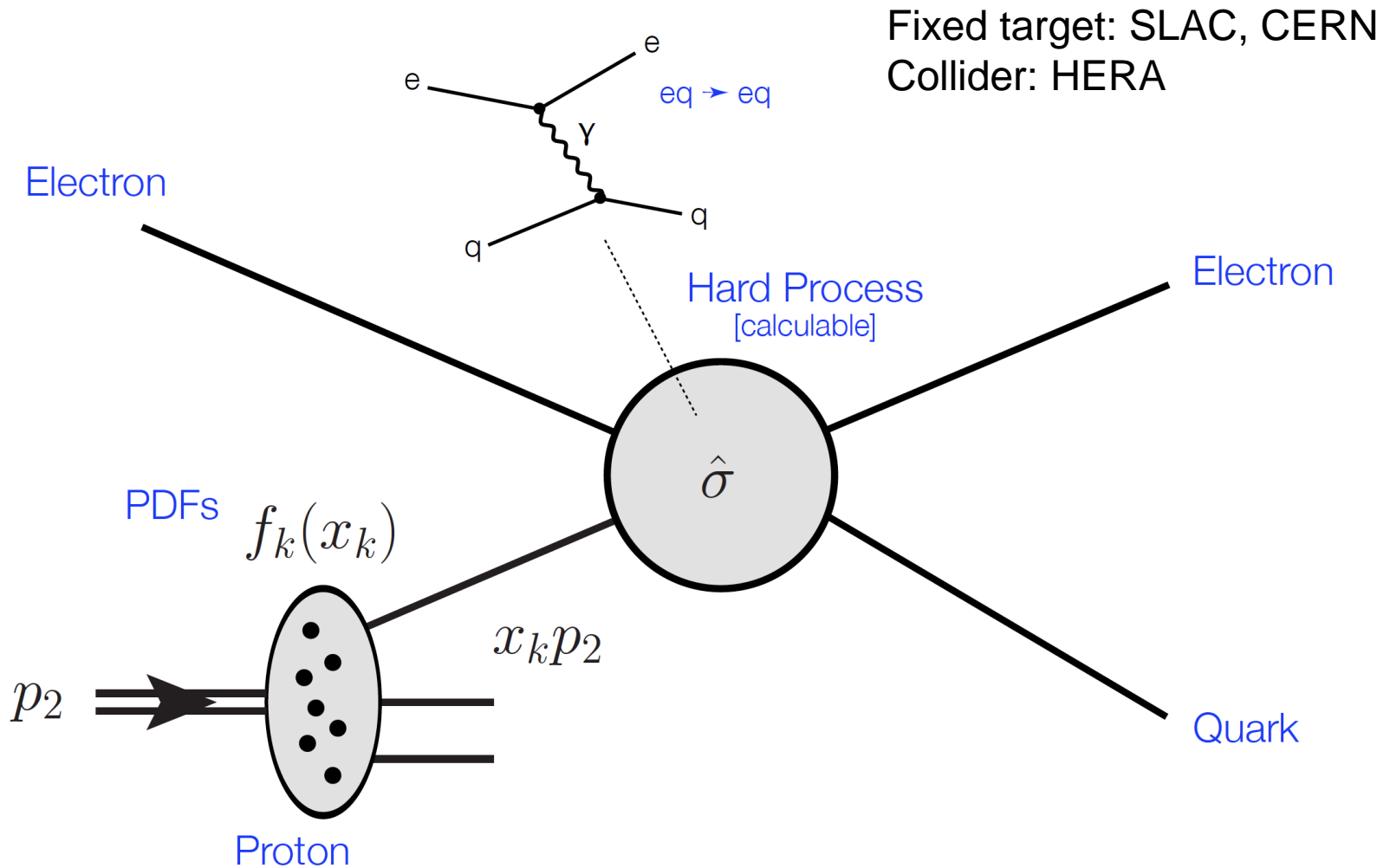
 $6 \left[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right]$ (bottom right)

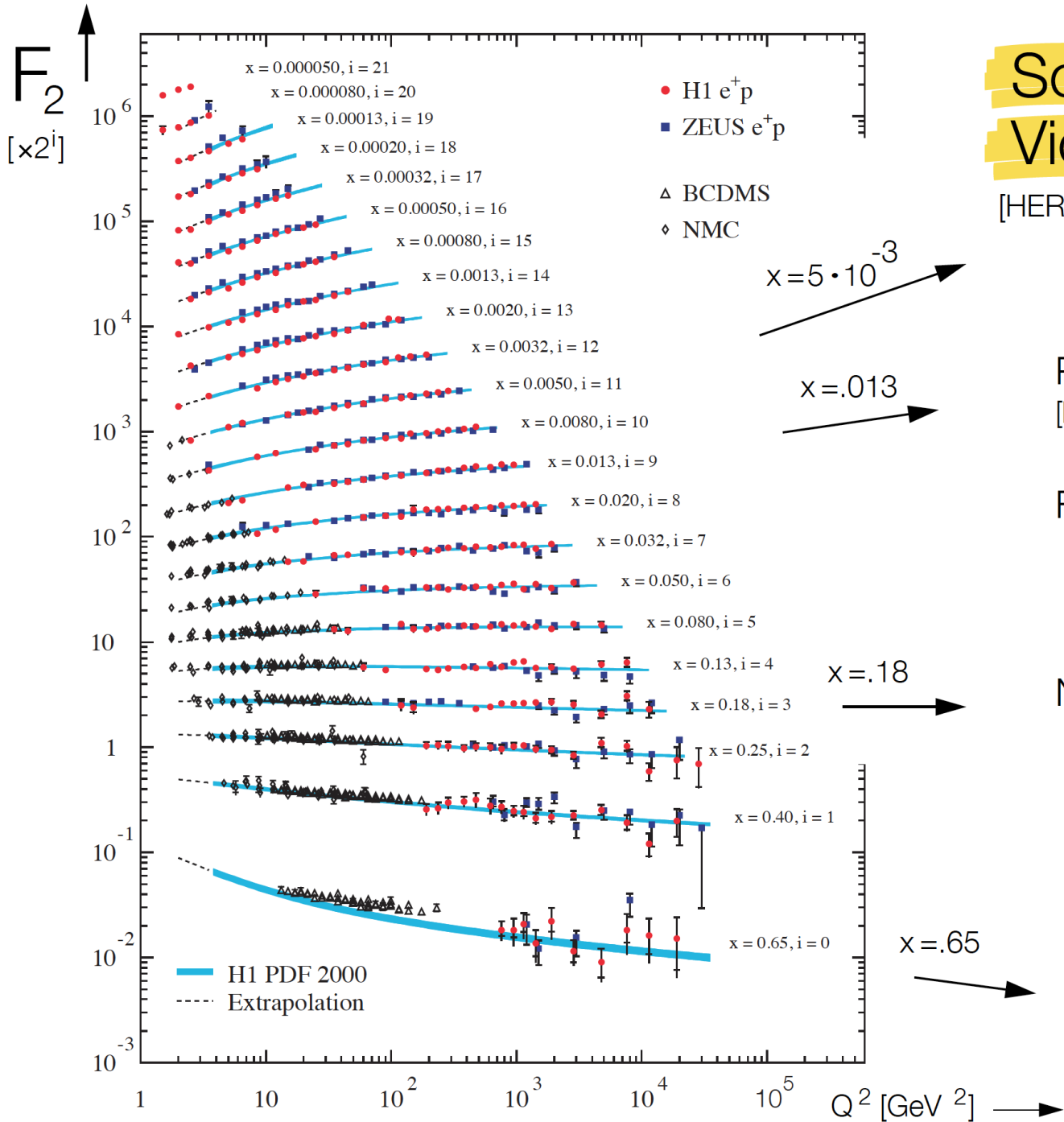
[z: momentum fraction of radiated parton]

QCD & parton densities



Lepton-proton scattering





Scaling Violations

[HERA & fixed target data]

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

$x = .013$

Precision: 2-3%
[bulk region]

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

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

$x = .18$

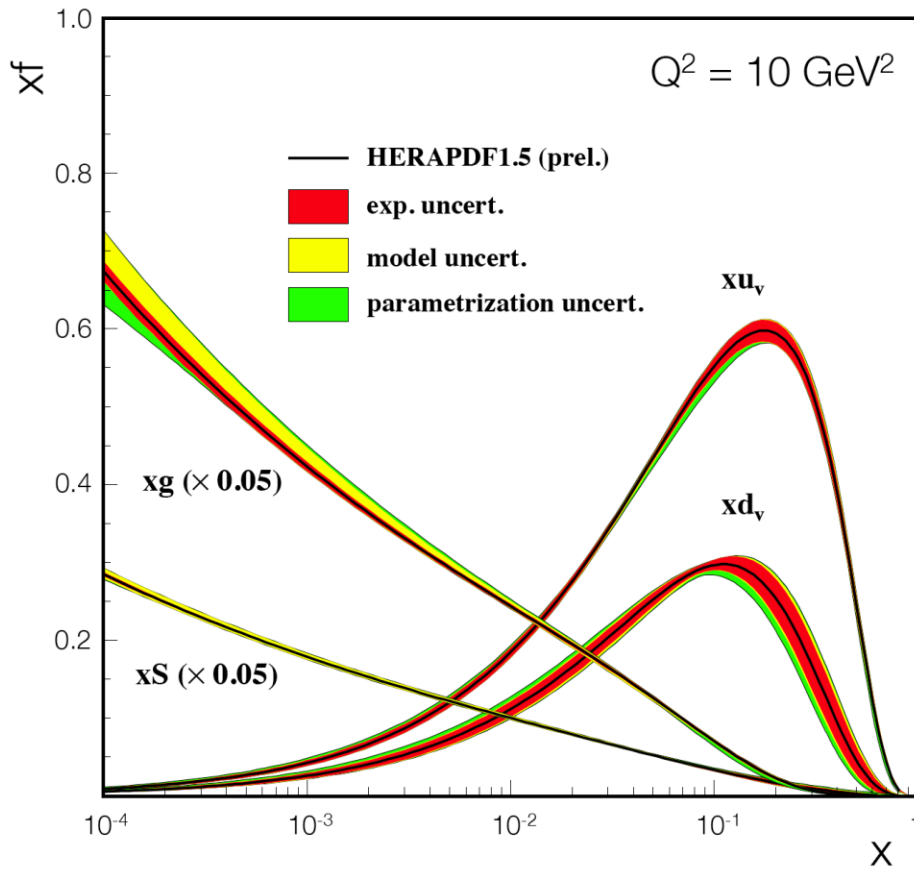
NLO QCD Fits:

- Quark densities
- Gluon density
- Strong coupling α_s

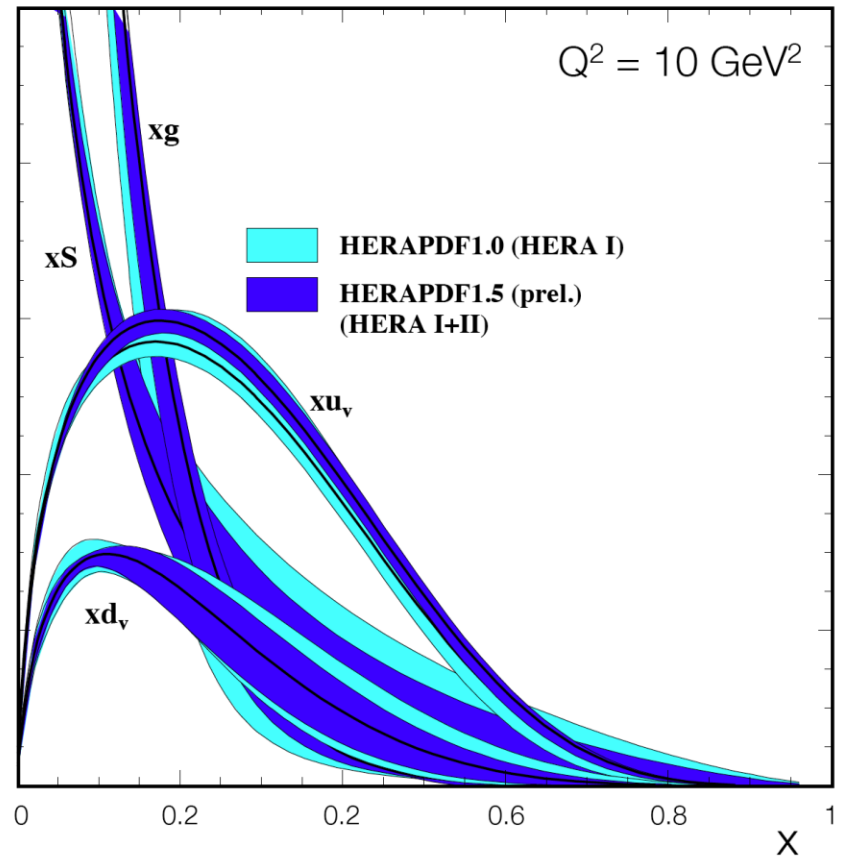
$x = .65$

Proton parton densities

H1 and ZEUS HERA I+II Combined PDF Fit

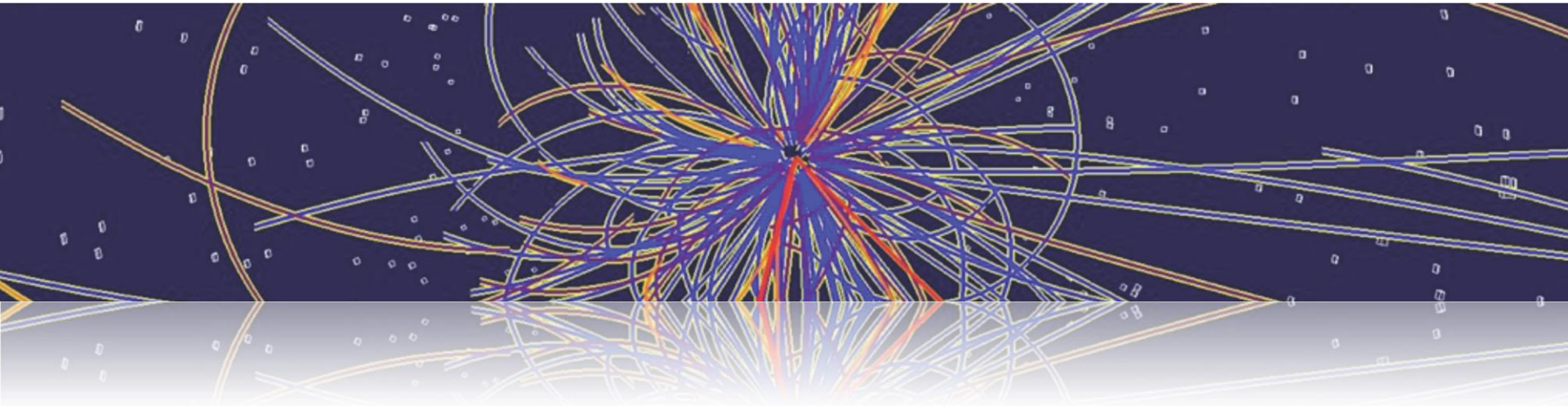


H1 and ZEUS Combined PDF Fit

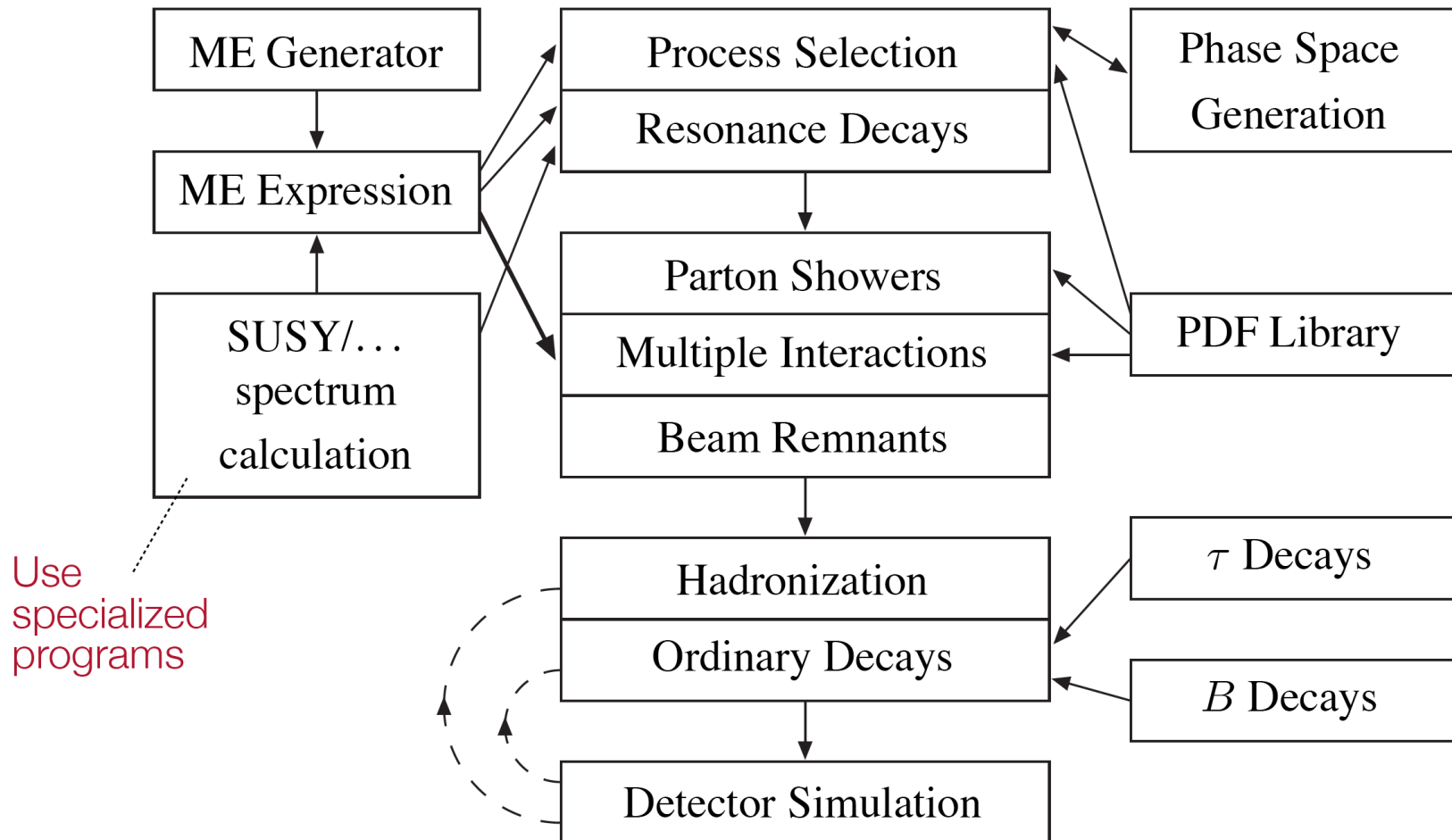


HERA Structure Functions Working Group July 2010

Monte Carlo Generators



Monte Carlo overview



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 ...]

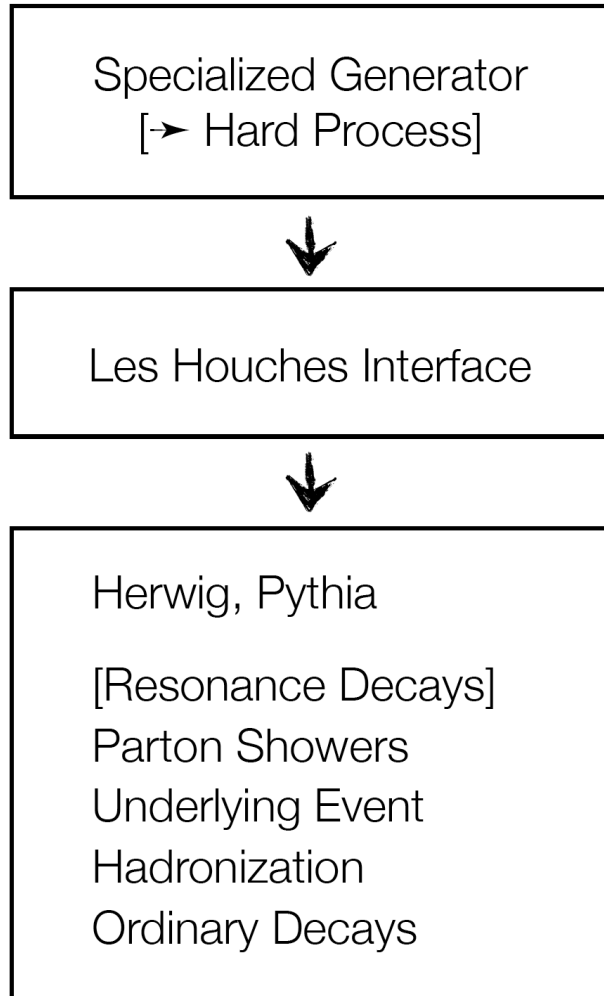
- provide correct spin correlations often absent in Pythia ...
[e.g. top produced unpolarized, while $t \rightarrow bW \rightarrow b\nu$ decay correct]

- 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 : $W/Z + \leq 6j$,
 $nW + mZ + kH + \leq 3j$, ...

AMEGIC++ : generic LO

CompHEP : generic LO

GRACE : generic LO
[+Bases/Spring] [+ some NLO loops]

GR@PPA : bbbb

MadCUP : $W/Z+ \leq 3j$, ttbb

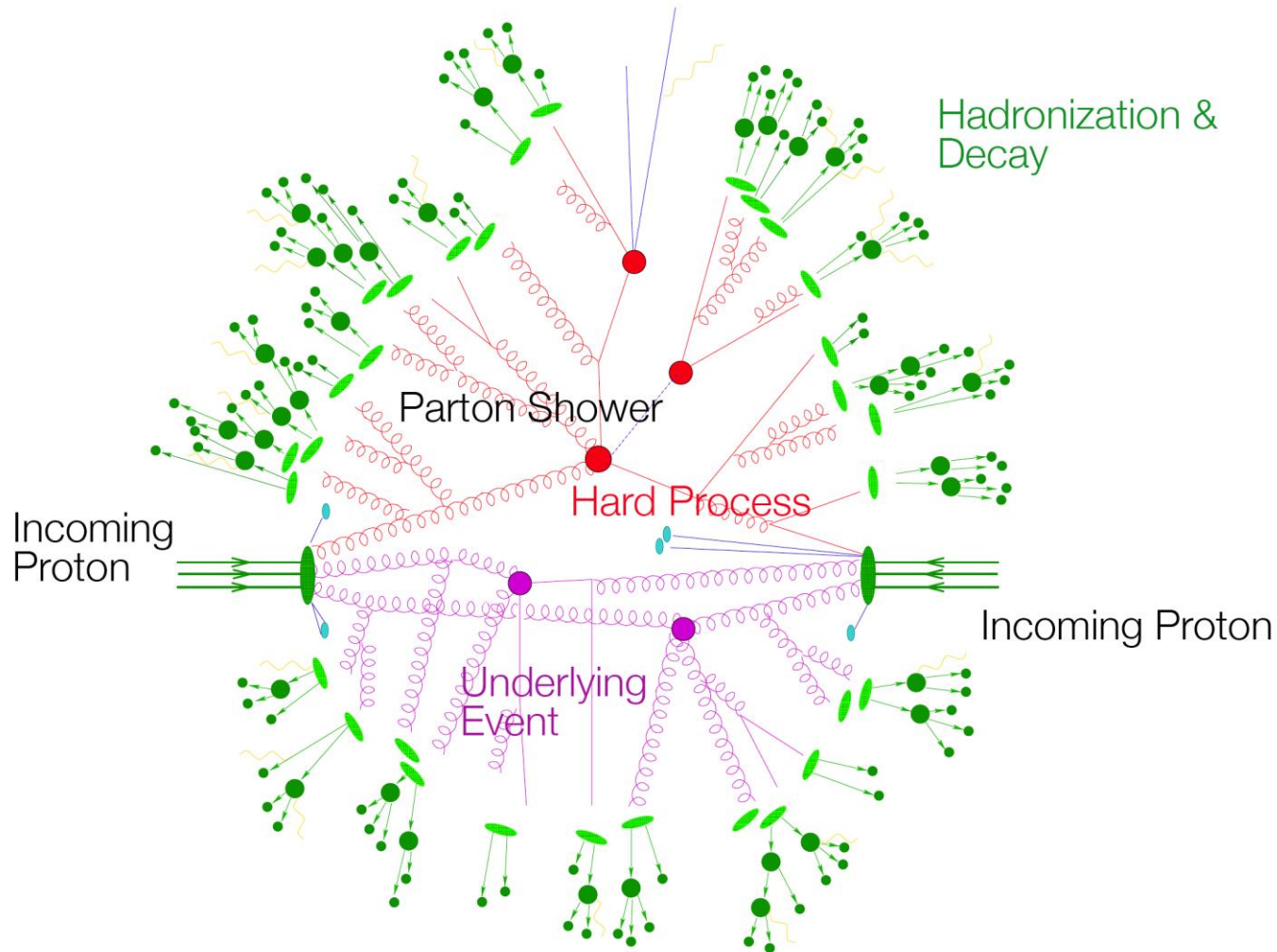
HELAS & MadGraph : generic LO

MCFM : NLO $W/Z+ \leq 2j$,
 $WZ, WH, H+ \leq 1j$

O'Mega & WHIZARD : generic LO

VECBOS : $W/Z+ \leq 4j$

From Partons to Jets



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

Parton splitting

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

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

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

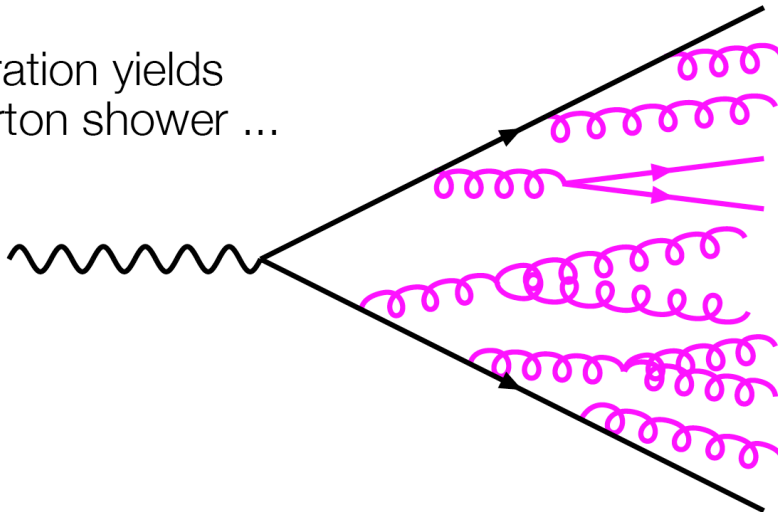
Same splitting functions
as used for PDF evolution

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

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

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

Iteration yields
parton shower ...



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

Details model-dependent

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

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:

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

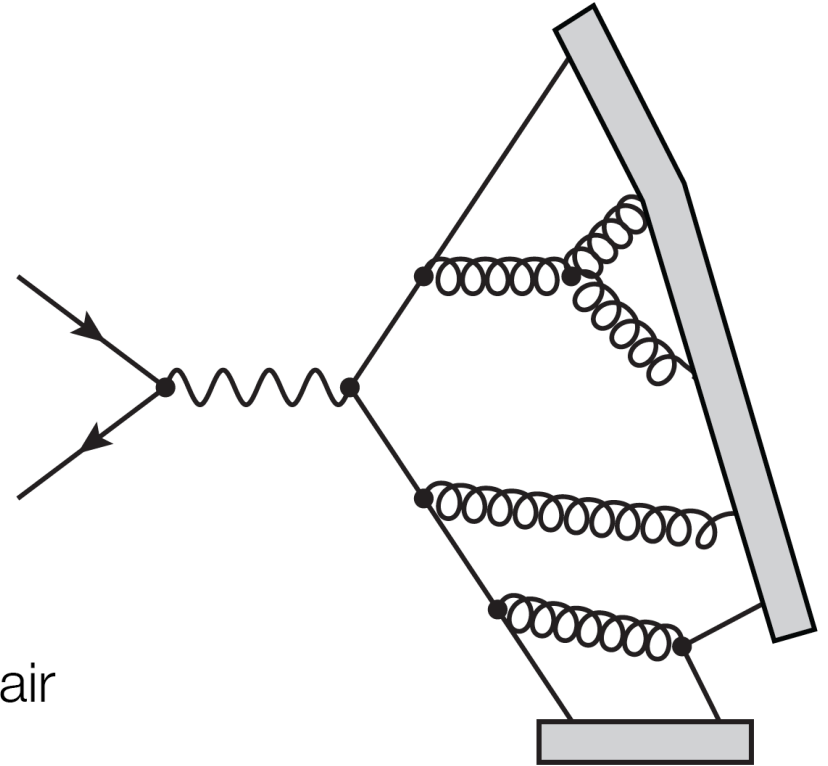
String formation between initial quark-antiquark pair

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

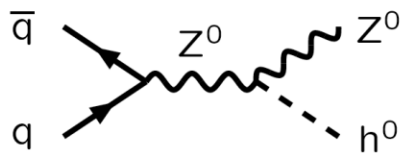
Overview of MC generators

Structure of basic generator process [by order of consideration]

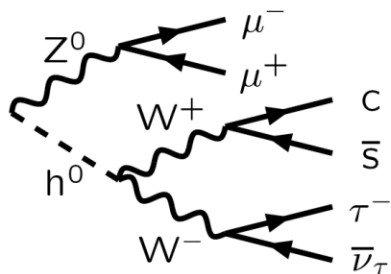
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled'; at small

Matrix elements (ME)

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

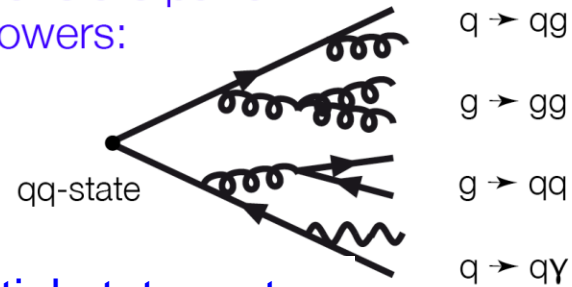


2. Resonance decays:
Includes particle correlations

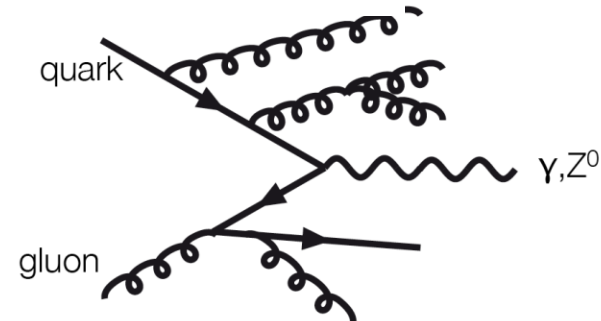


Parton Shower (PS)

3. Final-state parton showers:



4. Initial-state parton showers:



[from G.Herten]

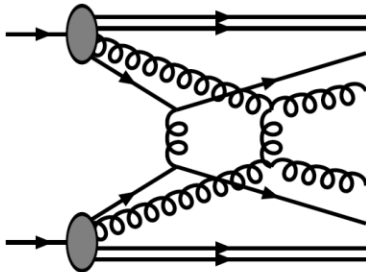
Overview of MC generators

Structure of basic generator process [by order of consideration]

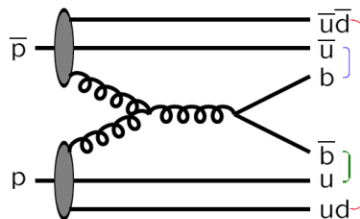
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modeled'; at small

Underlying Event (UE)

5. Multi-parton interaction:

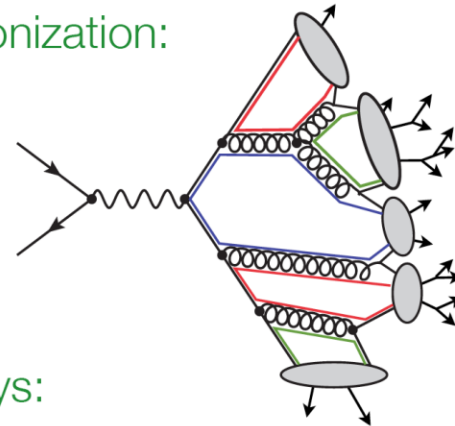


6. Beam remnants:

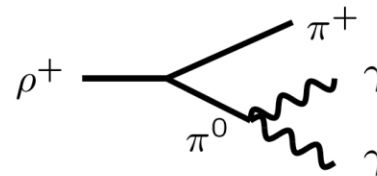


Stable Particle State

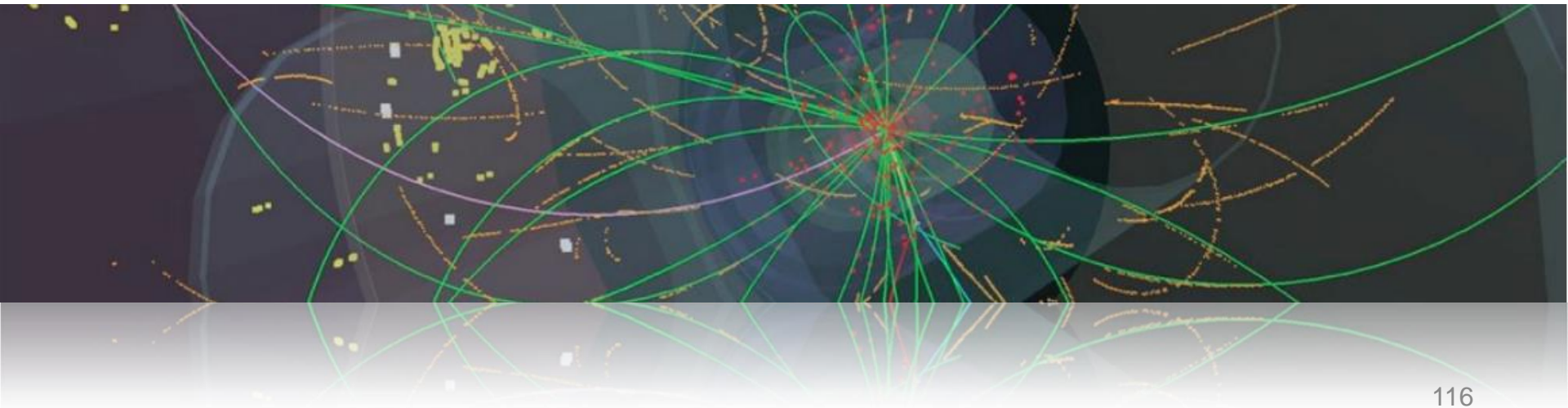
7. Hadronization:



8. Decays:



Luminosity and cross-section measurements



Cross section & Luminosity

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

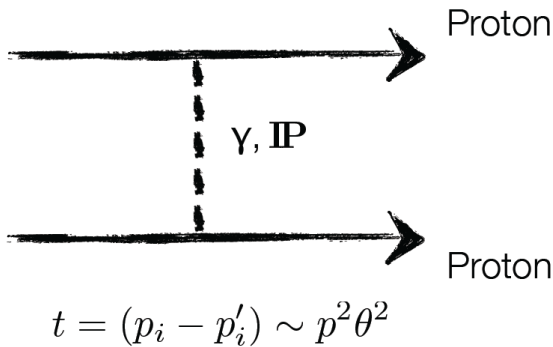
Event Rate
[Measured]

Luminosity
[Machine parameter]

Cross Section

Luminosity and elastic scattering

Elastic Scattering:



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:

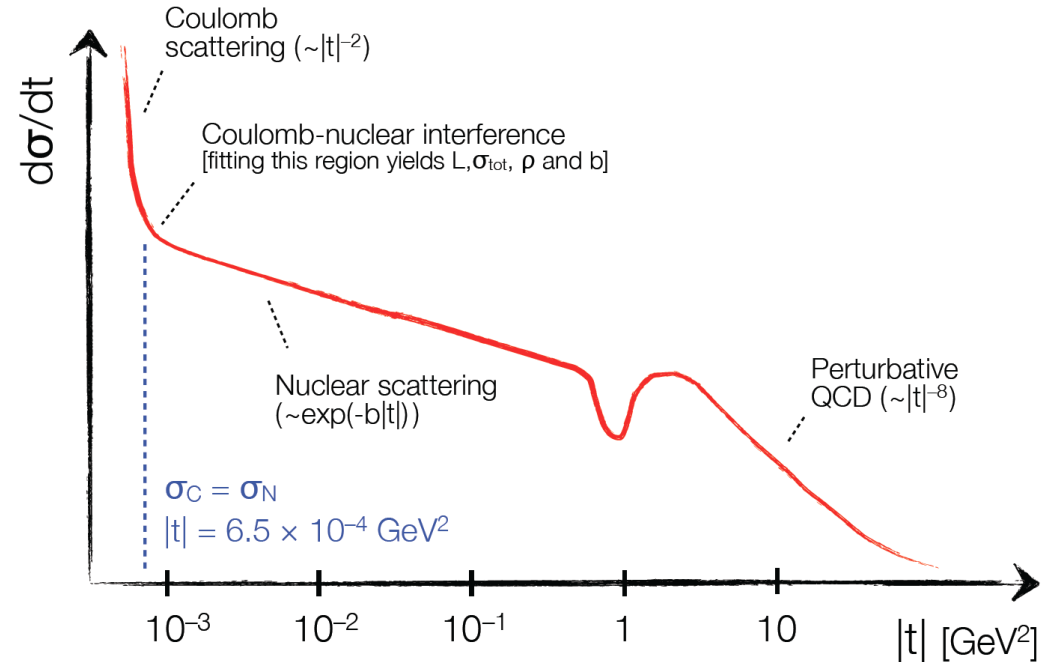
$$\frac{dN}{dt} = L \left(\underbrace{\frac{4\pi\alpha^2}{|t|^2}}_{\text{Coulomb Scattering}} - \underbrace{\frac{\alpha\rho\sigma_{\text{tot}} e^{-\frac{b|t|}{2}}}{|t|}}_{\text{Coulomb/nuclear Interference}} + \underbrace{\frac{\sigma_{\text{tot}}^2 (1 + \rho^2) e^{-b|t|}}{16\pi}}_{\text{Nuclear Scattering}}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

with:

ρ : ratio of the real to imaginary part of the elastic forward amplitude

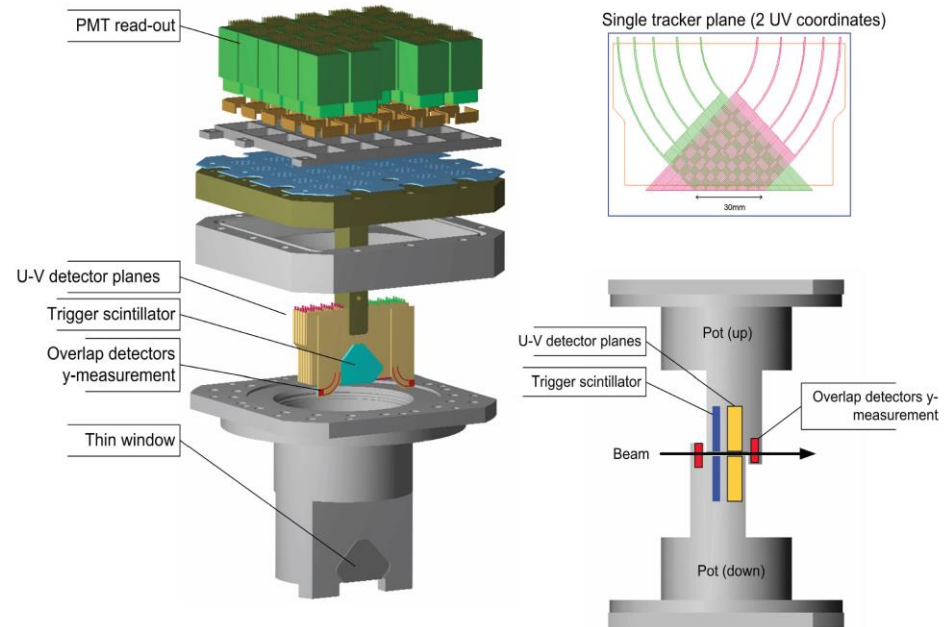
b : nuclear slope

σ_{tot} : total $pp \rightarrow X$ cross section

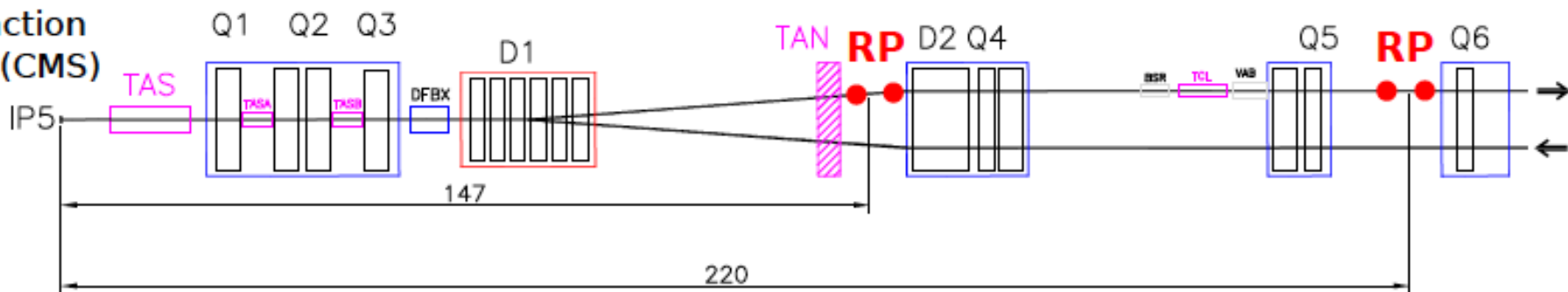


Roman Pots (Totem and Alfa)

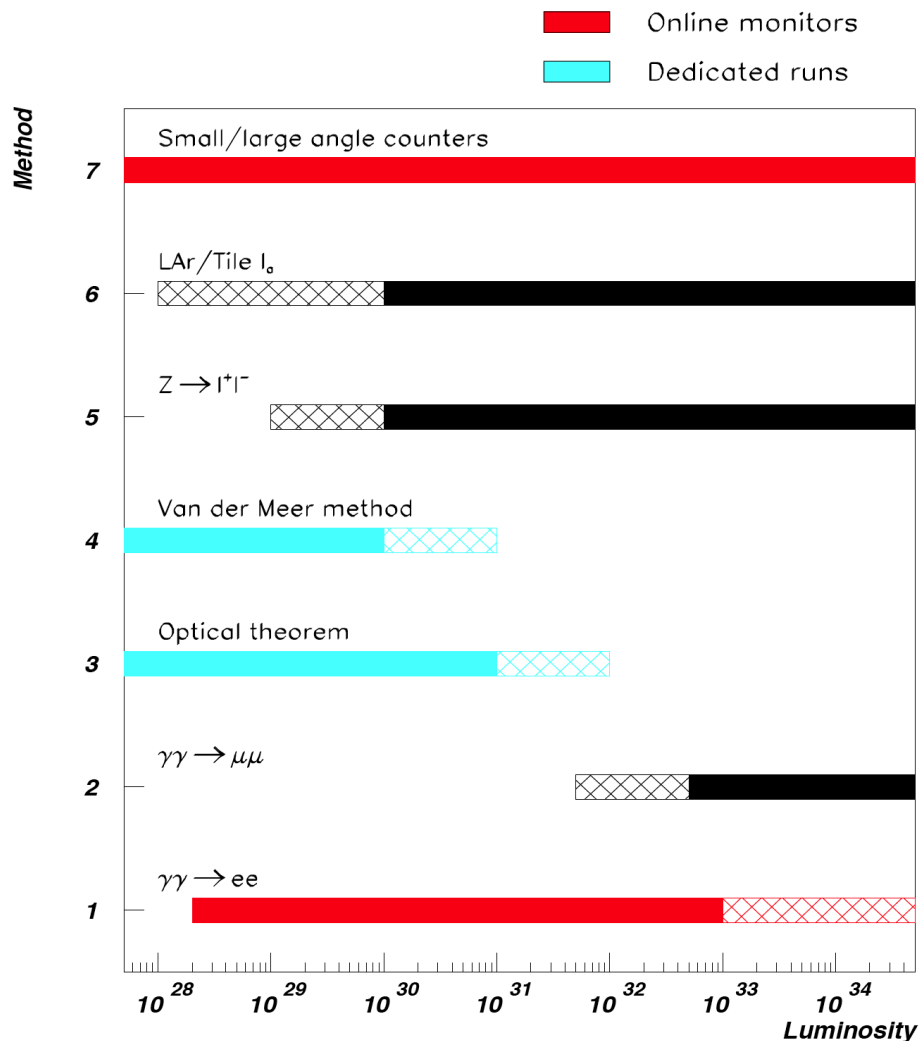
- Measurement of p-p elastic scattering
- Roman Pots used to move detectors near to stable beam.



Interaction point (CMS)



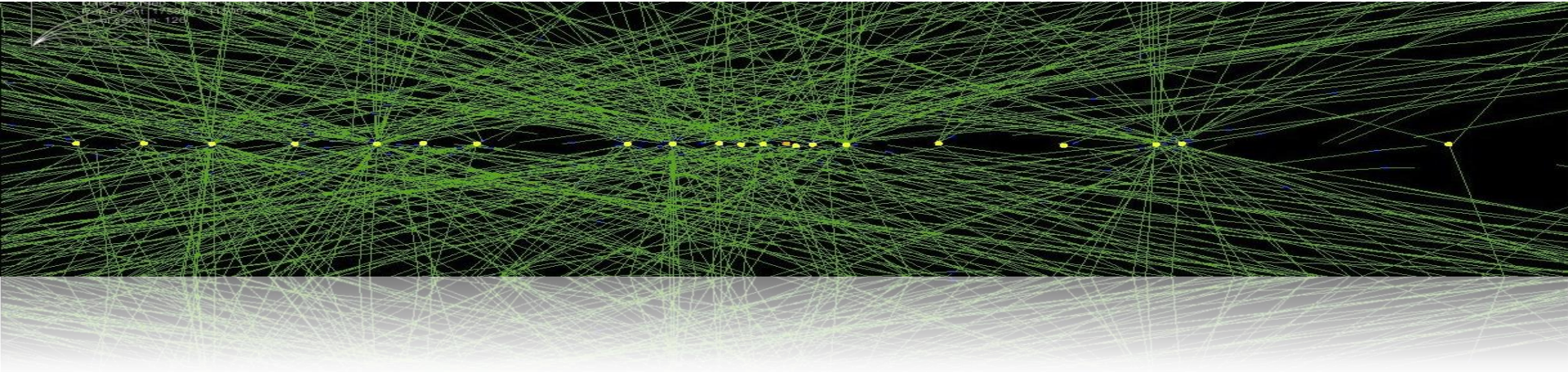
Luminosity determination @ LHC



Methods as summarized in ATLAS TDR

[ATLAS Technical Design Report, Vol. I]

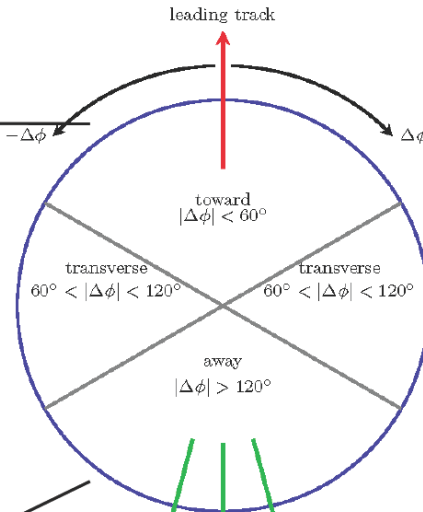
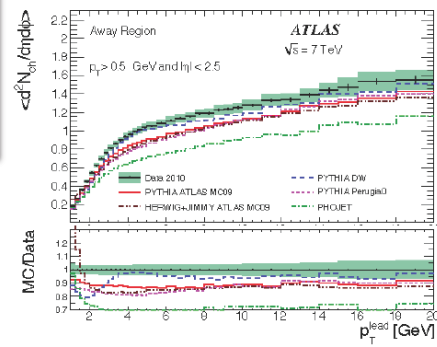
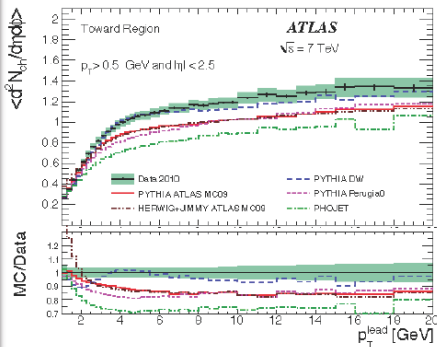
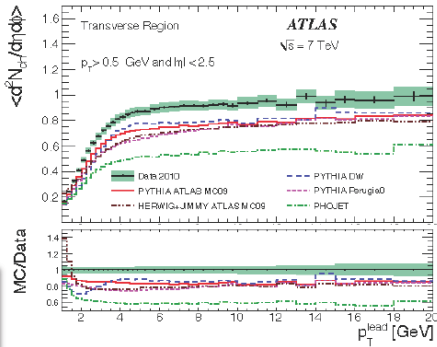
Minimum bias events



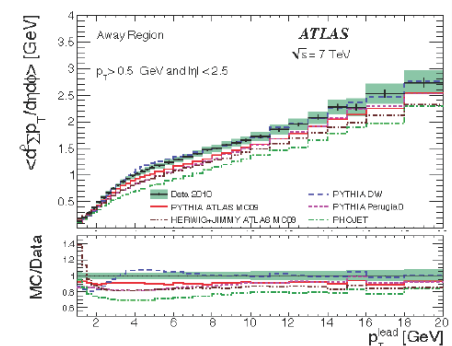
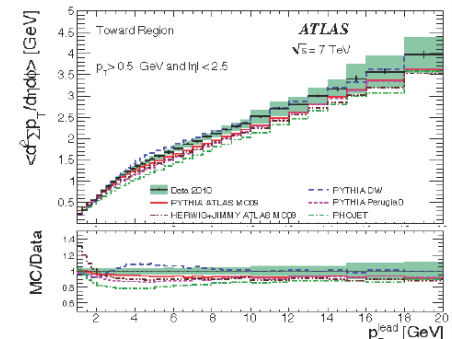
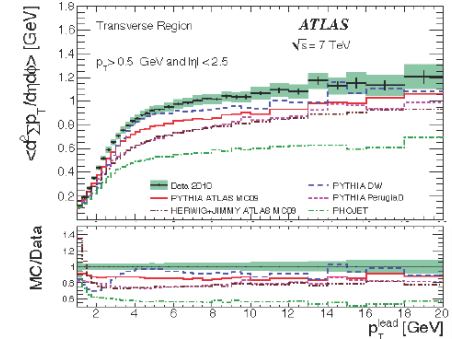
Underlying event

Particle momentum flow in regions defined wrt leading track

Multiplicity vs P_T



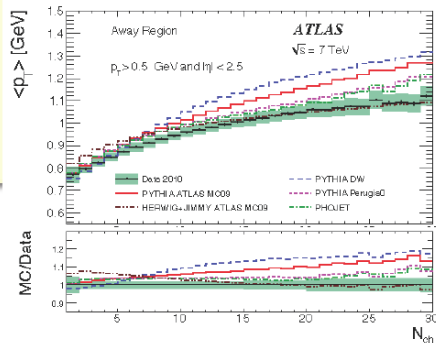
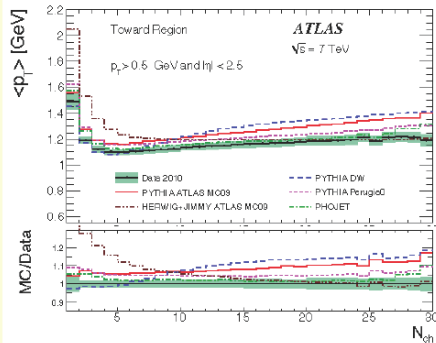
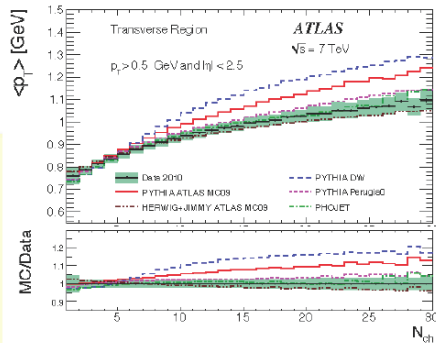
arXiv:1012.0791



Sum P_T vs P_T

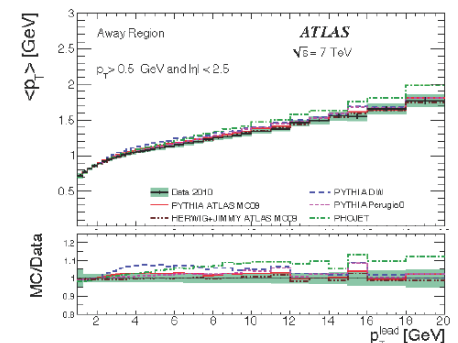
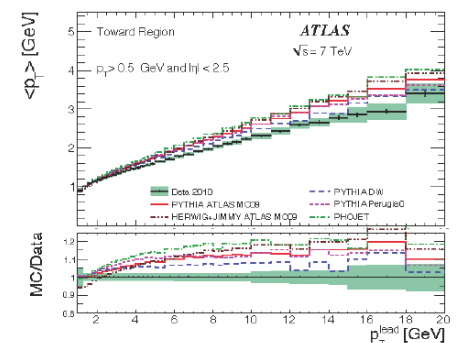
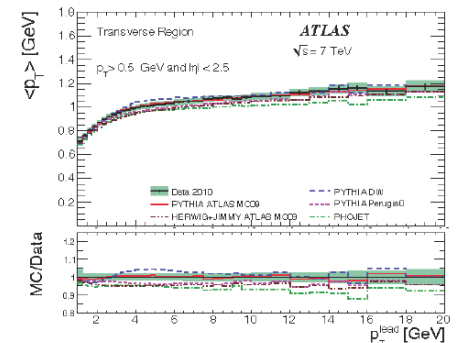
Underlying event

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

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