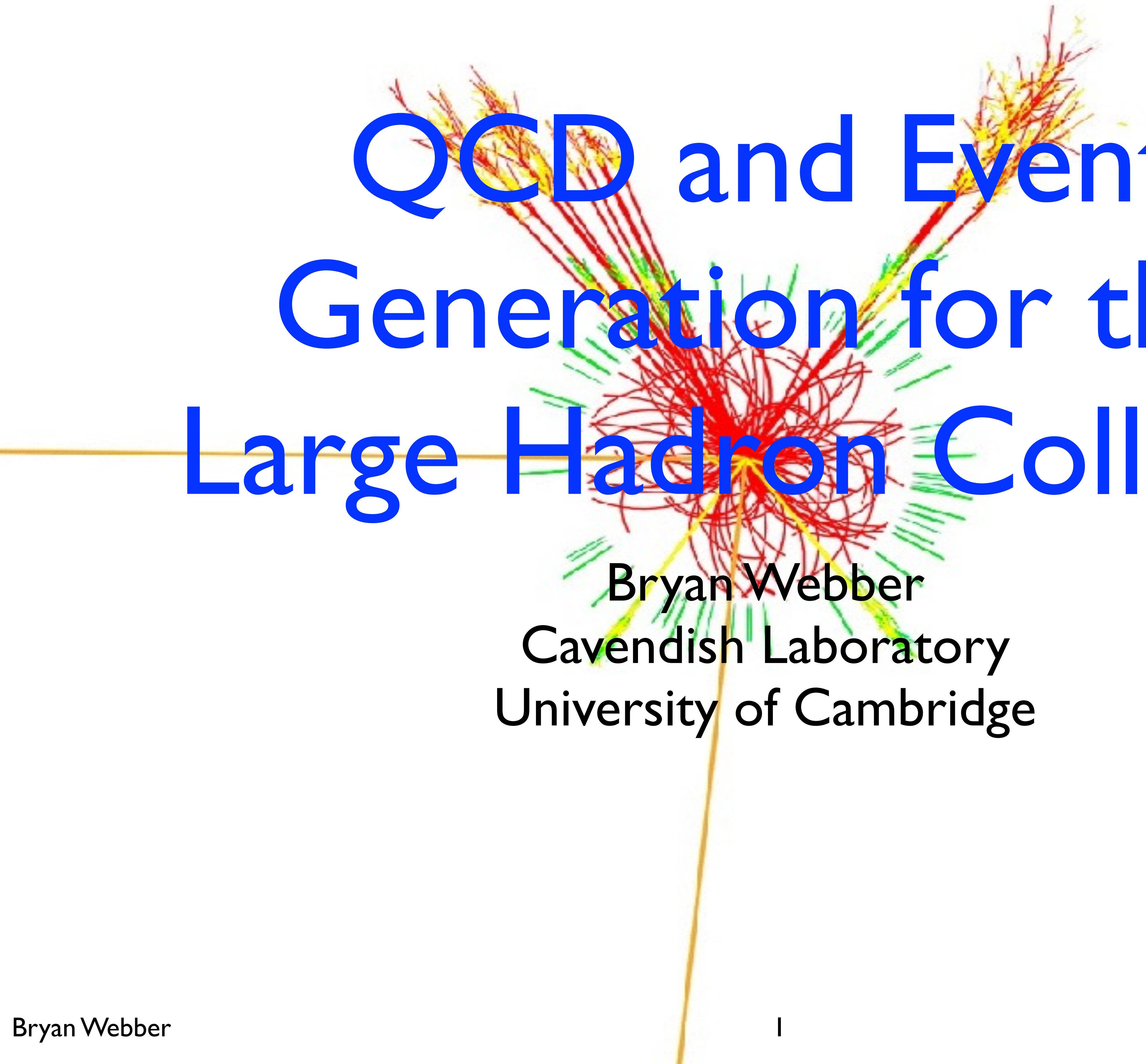
QCD and Event Generation for the Large Hadron Collider



Bryan Webber
Cavendish Laboratory
University of Cambridge

Higgs Decays

Higgs decays

HXSWG v.3, 1307.1347

	Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
56.1%	H → bb	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
		126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
		130	2.42	−2.4% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
6.2%	$H \to \tau^+\tau^-$	122	$2.51 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+2.0% −2.0%
		126	$2.59 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
		130	$2.67 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
0.02%	$H \to \mu^+\mu^-$	122	$8.71 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
		126	$8.99 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
		130	$9.27 \cdot 10^{-4}$	+0.1% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.0%	+2.0% −2.0%
2.8%	$H \to c\bar{c}$	122	$1.16 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.0%	+0.0% −0.1%	+2.0% −2.0%
		126	$1.19 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
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8.5%	H → gg	122	$3.25 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
		126	$3.57 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
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0.23%	$H \to \gamma\gamma$	122	$8.37 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
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0.16%	$H \to Z\gamma$	122	$4.74 \cdot 10^{-3}$	+0.0% −0.1%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+5.0% −5.0%
		126	$6.84 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
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2.9%	H → ZZ	122	$7.30 \cdot 10^{-2}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
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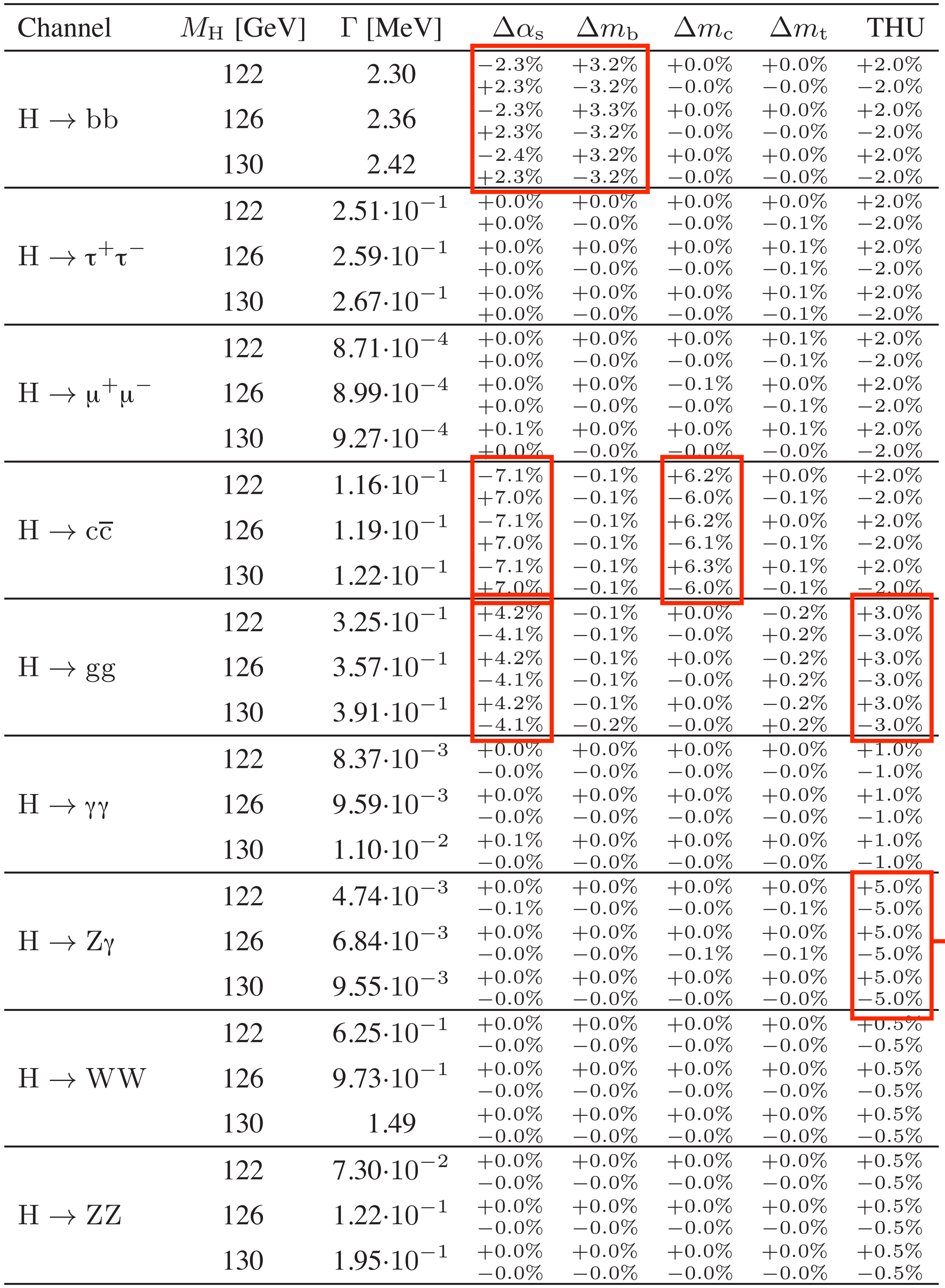
$\Gamma_{tot}(126) = 4.21$ MeV

Theoretical uncertainty: from scale variation and missing higher orders (not uncertainty in m_H)

Parametric uncertainties from QCD coupling and quark masses

Higgs decays

HXSWG v.3, 1307.1347



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6.2%	$\mathrm{H} \to \tau^+\tau^-$	122	$2.51 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+2.0% −2.0%
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8.5%	$\mathrm{H} \to \mathrm{gg}$	122	$3.25 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
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23.1%	$\mathrm{H} \to \mathrm{WW}$	122	$6.25 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
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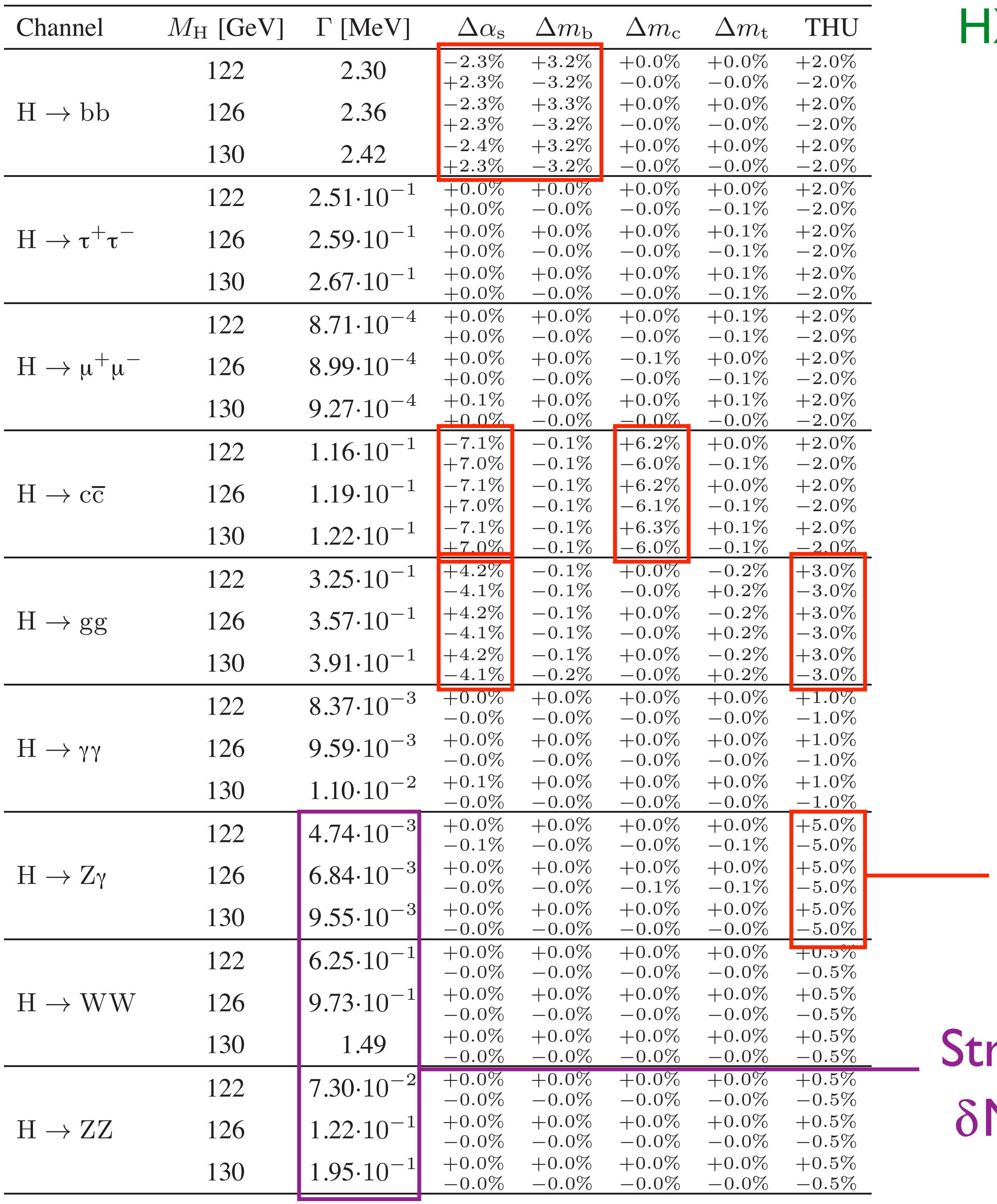
Uncertainties > 2%
(mostly QCD)

Unknown EW HO

$\Gamma_{\mathrm{tot}}(126) = 4.21$ MeV

Higgs decays

HXSWG v.3, 1307.1347



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		130	$9.27 \cdot 10^{-4}$	+0.1% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.0%	+2.0% −2.0%
2.8%	$H \to c\bar{c}$	122	$1.16 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.0%	+0.0% −0.1%	+2.0% −2.0%
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8.5%	H → gg	122	$3.25 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
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23.1%	H → WW	122	$6.25 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
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2.9%	H → ZZ	122	$7.30 \cdot 10^{-2}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
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$\Gamma_{tot}(126) = 4.21$ MeV

Uncertainties > 2%
(mostly QCD)

Unknown EW HO

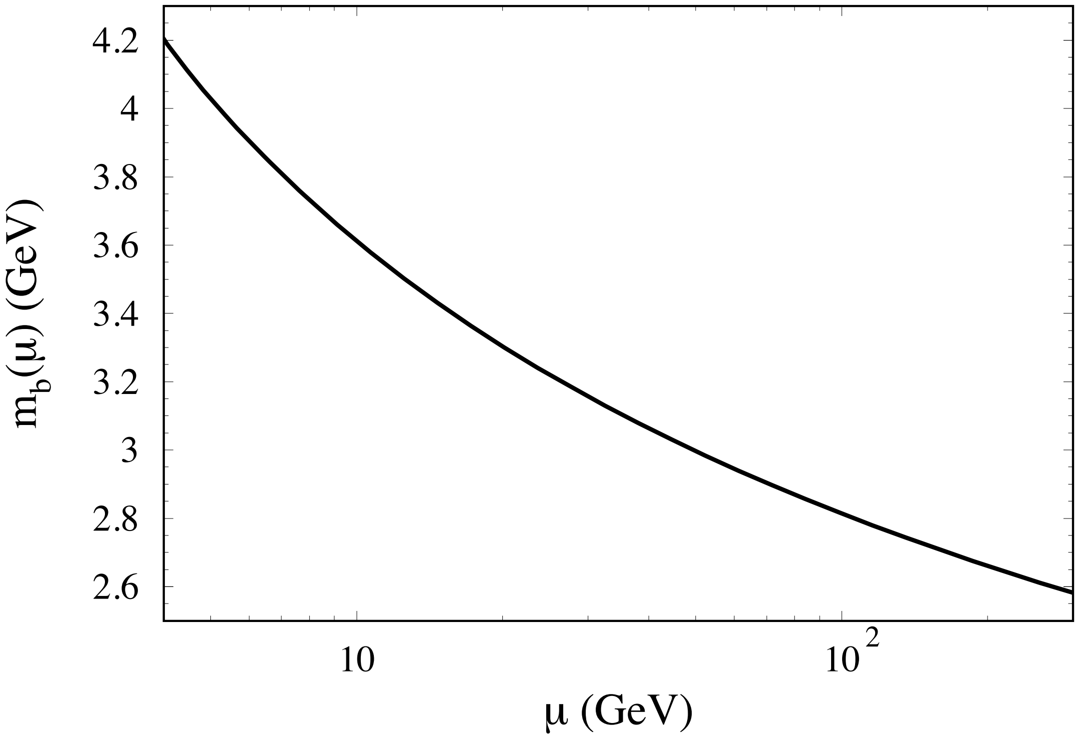
Strong mass dependence
$\delta M_H = 400$ MeV => ~5%

Running quark mass

- Couplings and masses (parameters in Lagrangian) must be renormalised, hence scale (and scheme) dependent

$$\mu^2\frac{d\alpha_s}{d\mu^2} = \beta(\alpha_s)\alpha_s = -\alpha_s^2(\beta_0+\beta_1\alpha_s+\ldots)$$

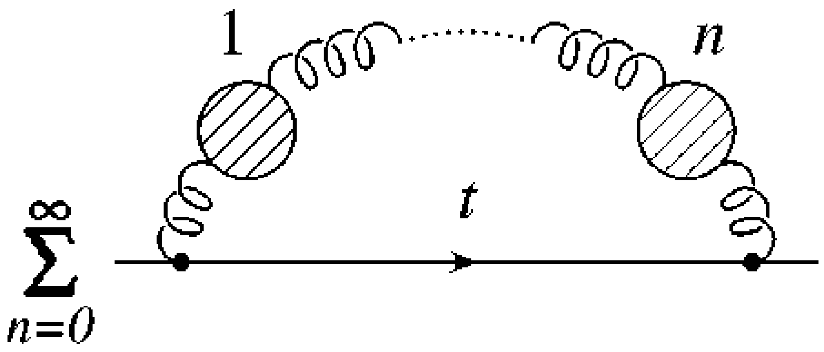
$$\mu^2\frac{dm_q}{d\mu^2} = \gamma(\alpha_s)m_q = -\alpha_s(\gamma_0+\gamma_1\alpha_s+\ldots)m_q \Rightarrow \frac{dm_q}{m_q} = \frac{d\alpha_s}{\alpha_s}\frac{\gamma(\alpha_s)}{\beta(\alpha_s)}$$



$$\boxed{m_q(\mu) = m_q(\mu_0)\left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\frac{\gamma_0}{\beta_0}}\left\{1+\left(\frac{\gamma_1}{\beta_0}-\frac{\beta_1\gamma_0}{\beta_0^2}\right)[\alpha_s(\mu)-\alpha_s(\mu_0)]+\ldots\right\}}$$

Pole quark mass

$$D(\not{p}) = \frac{i}{\not{p} - m_q - \Sigma(\not{p})}$$



$$\not{p}_{\rm pole} = m_q + \Sigma(\not{p}) = m_q + \Sigma^{(1)}(m_q) + \ldots$$

$$c_n \sim 2^n n! \sim (2n/e)^n$$

$$\Sigma^{(1)}(m_q) = \frac{16 m_q}{3\beta_0} \sum_{n=0}^{\infty} c_n\, a^{n+1}$$

$$a = \frac{\beta_0 \alpha_{\rm s}(m_q)}{4\pi} \sim \frac{1}{\log(m_q^2/\Lambda^2)} \equiv \frac{1}{L}$$

Asymptotic expansion: sum to smallest term (n~L/2)

Ambiguity ~ smallest term ($c_n\, a^{n+1} \sim e^{-L/2} \sim \Lambda/m_q$)

$$m_{\rm pole} = m_q(m_q)\left\{1 + 0.4244\, \alpha_{\rm s}(m_q) + 0.835\, \alpha_{\rm s}^2(m_q) + 2.375\, \alpha_{\rm s}^3(m_q) + \ldots\right\} + \mathcal{O}(\Lambda)$$

Renormalon ambiguity

(There is no pole!)

Higgs → $q\bar{q}$

$$\Gamma(H \to q\bar{q}) = \frac{3\sqrt{2}}{8\pi} G_F M_H m_q^2(M_H) \left[1 - \frac{4m_q^2(M_H)}{M_H^2}\right]^{\frac{3}{2}} [1 + 1.803\,\alpha_{\rm s}(M_H) + 2.953\,\alpha_{\rm s}^2(M_H) + \ldots]$$

(known to 4th order)

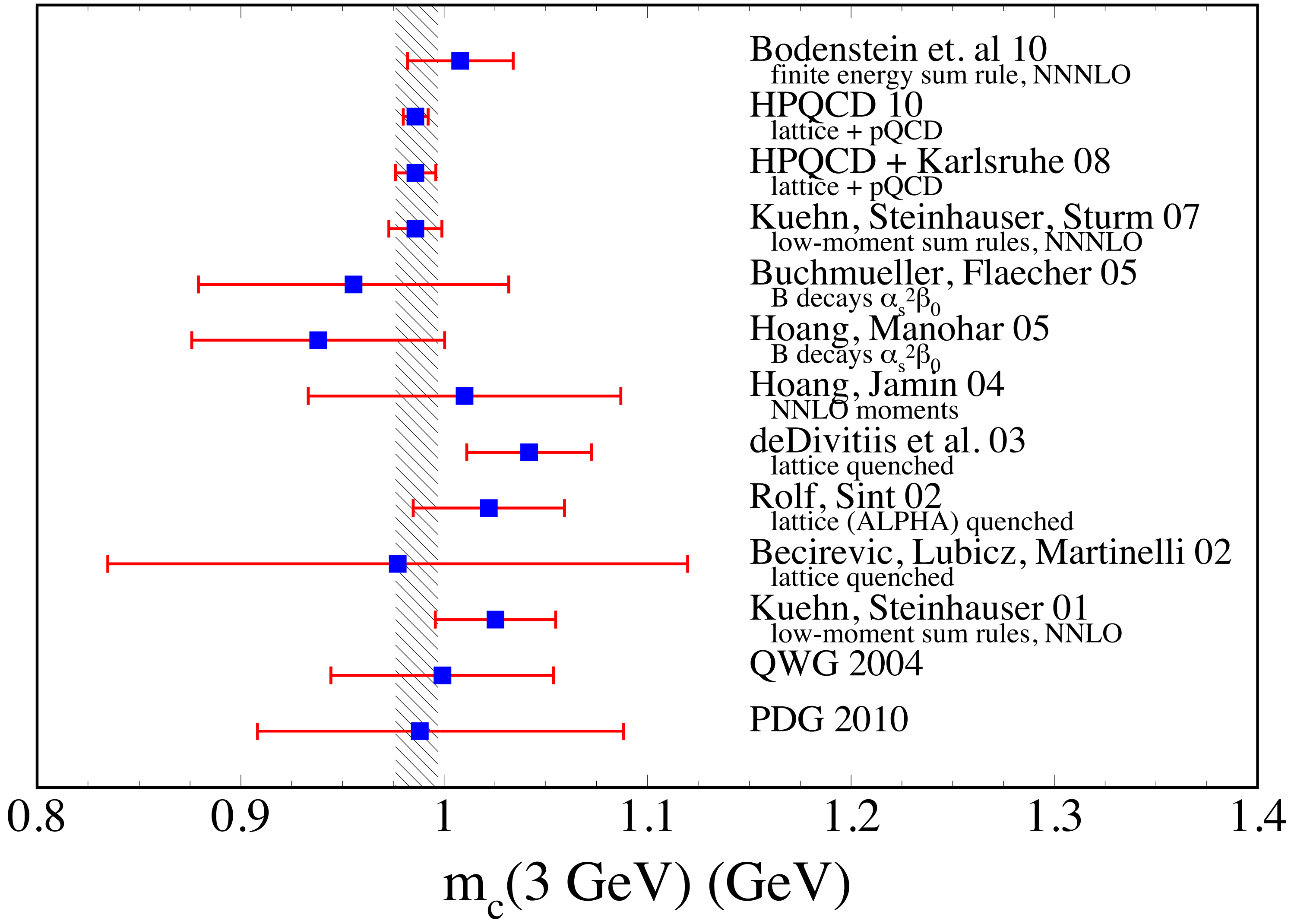
- Running of masses is enormously important!

$$\boxed{\begin{array}{c} m_b^2(M_H)/m_b^2(m_b) = (2.77/4.16)^2 = 0.442 \\ m_c^2(M_H)/m_c^2(m_c) = (0.612/1.27)^2 = 0.233 \end{array}}$$

- Γ_b affects all branching ratios!

$$\mathrm{BR(X)} = \frac{\Gamma_{\rm X}}{\Gamma_{\rm tot}} \longrightarrow \frac{\delta\,\mathrm{BR(X)}}{\mathrm{BR(X)}} = \frac{\delta\,\Gamma_{\rm b}}{\Gamma_{\rm tot}} = 0.56\frac{\delta\,\Gamma_{\rm b}}{\Gamma_{\rm b}}$$

Charm quark mass



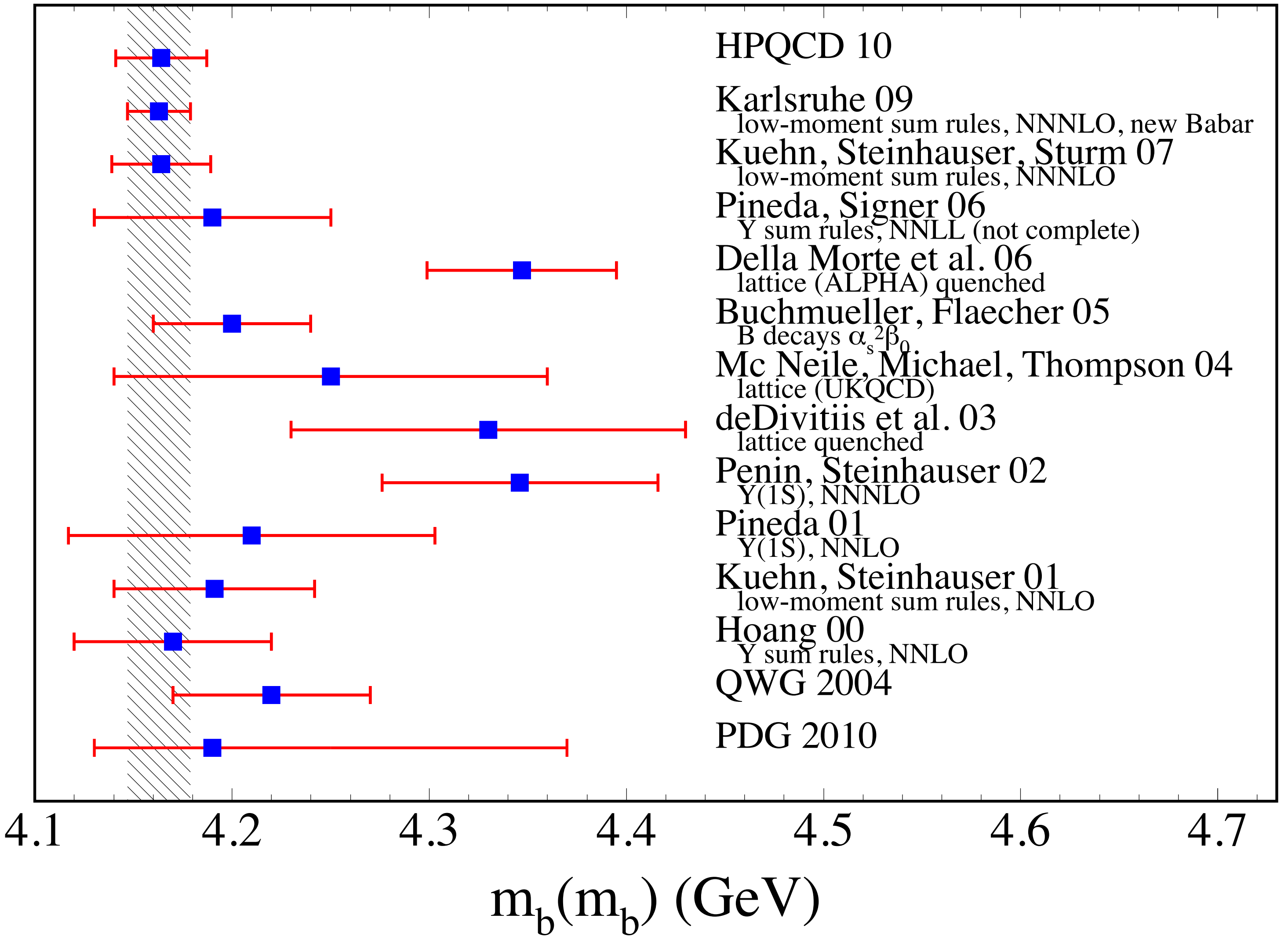
Kühn, 2013

$m_c(3\ \text{GeV}) = 0.986(6)\ \text{GeV}$

➡ $m_c(m_c) = 1.268(9)\ \text{GeV}$

➡ $m_c(M_H) = 0.612(5)\ \text{GeV}$

Bottom quark mass



Kühn, 2013

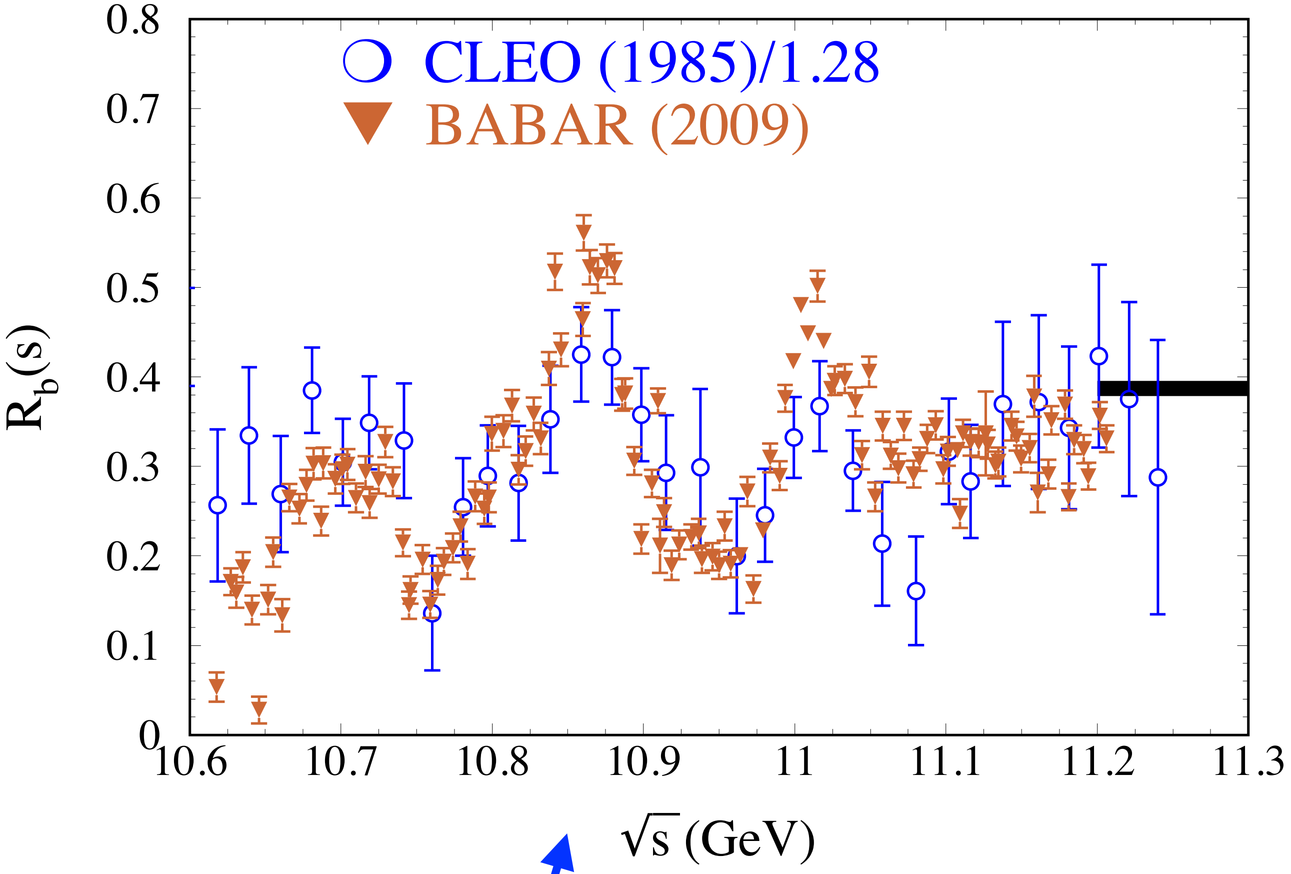
$m_b(10\ \text{GeV}) = 3.617(25)$ GeV

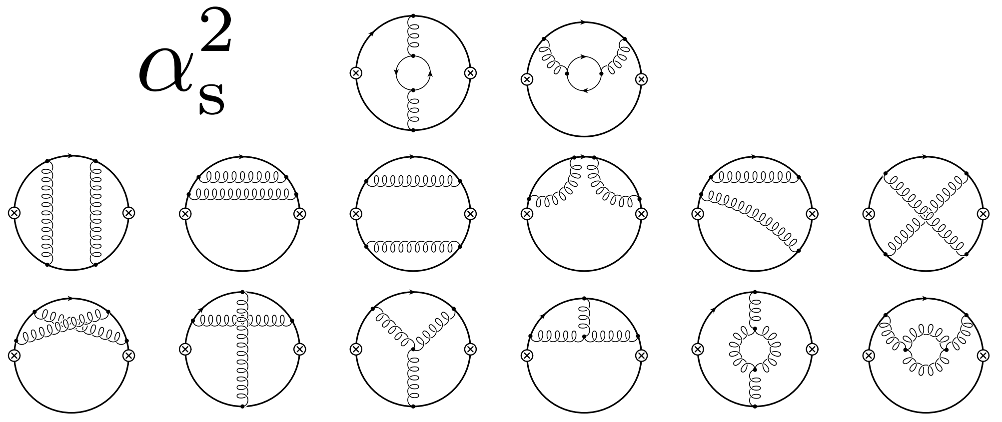
→ $m_b(m_b) = 4.164(30)$ GeV

→ $m_b(M_H) = 2.768(21)$ GeV

m_b from QCD sum rules

Chetyrkin et al., PRD80(2009)074010





$$\ldots + \alpha_s^3$$ (~700 diagrams)

$$\mathcal{M}_n = \int \frac{ds}{s^{n+1}} R_b(s) = \frac{9}{4} e_b^2 \left(\frac{1}{4 m_b^2(\mu)}\right)^n C_n(\alpha_s, \mu) \longrightarrow m_b(\mu) = \frac{1}{2} \left(\frac{9 e_b^2 C_n(\alpha_s, \mu)}{4 \mathcal{M}_n}\right)^{\frac{1}{2n}}$$

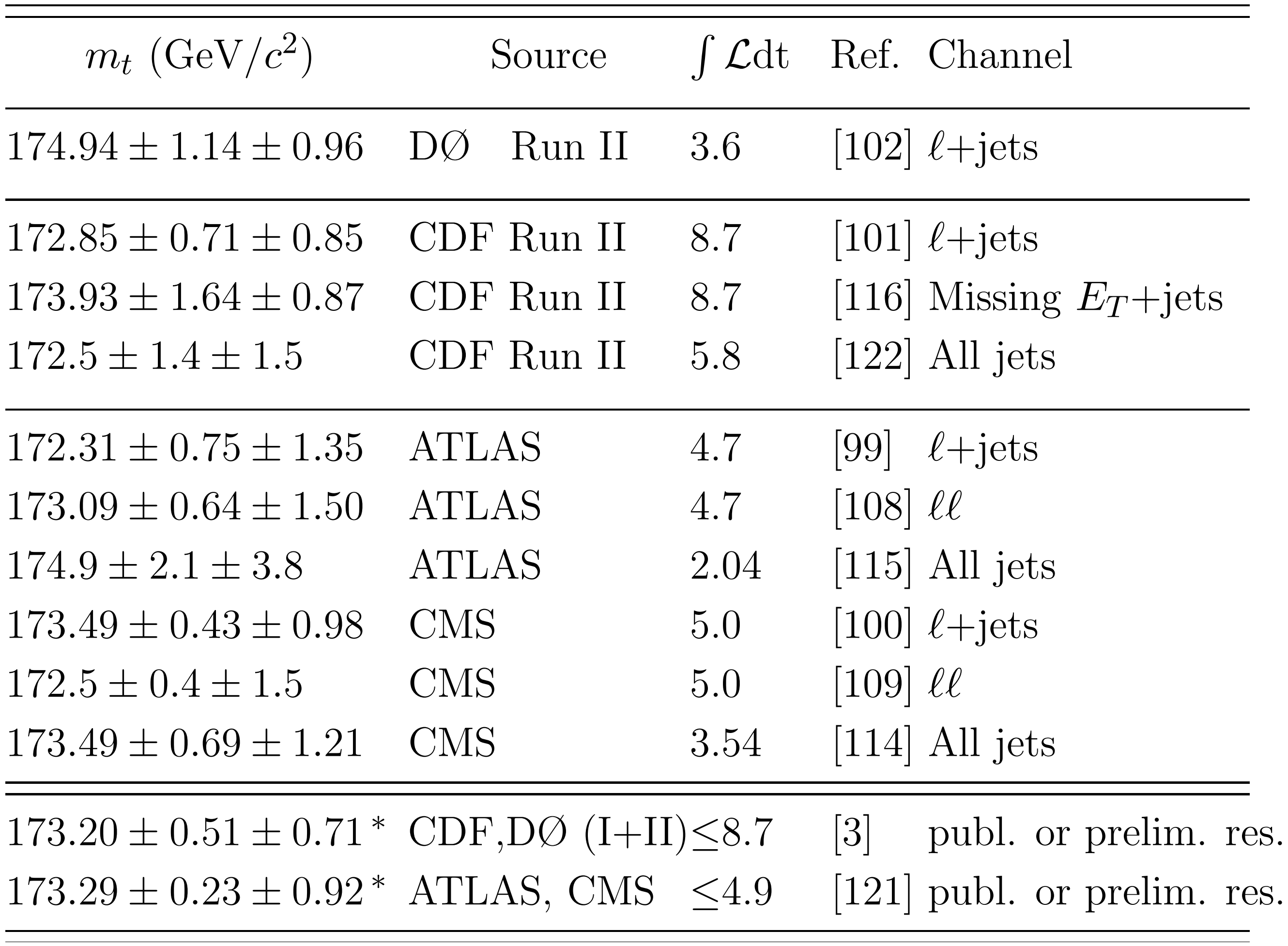
n	$m_b(10\,\mathrm{GeV})$	exp	α_s	μ	total	$m_b(m_b)$
1	3597	14	7	2	16	4151
2	3610	10	12	3	16	4163
3	3619	8	14	6	18	4172
4	3631	6	15	20	26	4183

$$\boxed{m_b(10\ \mathrm{GeV}) = 3.610(16)\ \mathrm{GeV}}$$

Top quark mass

“Direct” (≈pole mass?) measurements:

RPP 2013



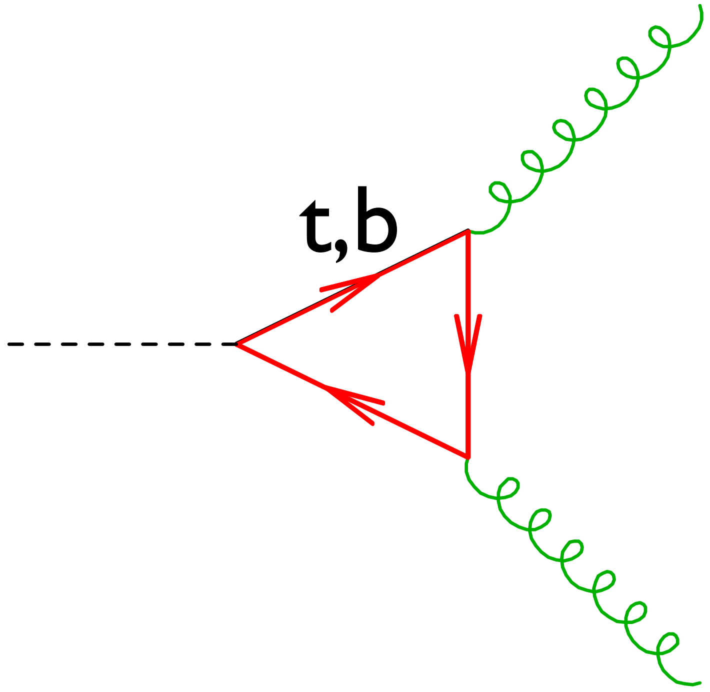
m_t (GeV/c^2)	Source	$\int \mathcal{L}dt$	Ref.	Channel
$174.94 \pm 1.14 \pm 0.96$	DØ Run II	3.6	[102]	ℓ+jets
$172.85 \pm 0.71 \pm 0.85$	CDF Run II	8.7	[101]	ℓ+jets
$173.93 \pm 1.64 \pm 0.87$	CDF Run II	8.7	[116]	Missing E_T+jets
$172.5 \pm 1.4 \pm 1.5$	CDF Run II	5.8	[122]	All jets
$172.31 \pm 0.75 \pm 1.35$	ATLAS	4.7	[99]	ℓ+jets
$173.09 \pm 0.64 \pm 1.50$	ATLAS	4.7	[108]	$\ell\ell$
$174.9 \pm 2.1 \pm 3.8$	ATLAS	2.04	[115]	All jets
$173.49 \pm 0.43 \pm 0.98$	CMS	5.0	[100]	ℓ+jets
$172.5 \pm 0.4 \pm 1.5$	CMS	5.0	[109]	$\ell\ell$
$173.49 \pm 0.69 \pm 1.21$	CMS	3.54	[114]	All jets
$173.20 \pm 0.51 \pm 0.71^*$	CDF,DØ (I+II)	≤ 8.7	[3]	publ. or prelim. res.
$173.29 \pm 0.23 \pm 0.92^*$	ATLAS, CMS	≤ 4.9	[121]	publ. or prelim. res.

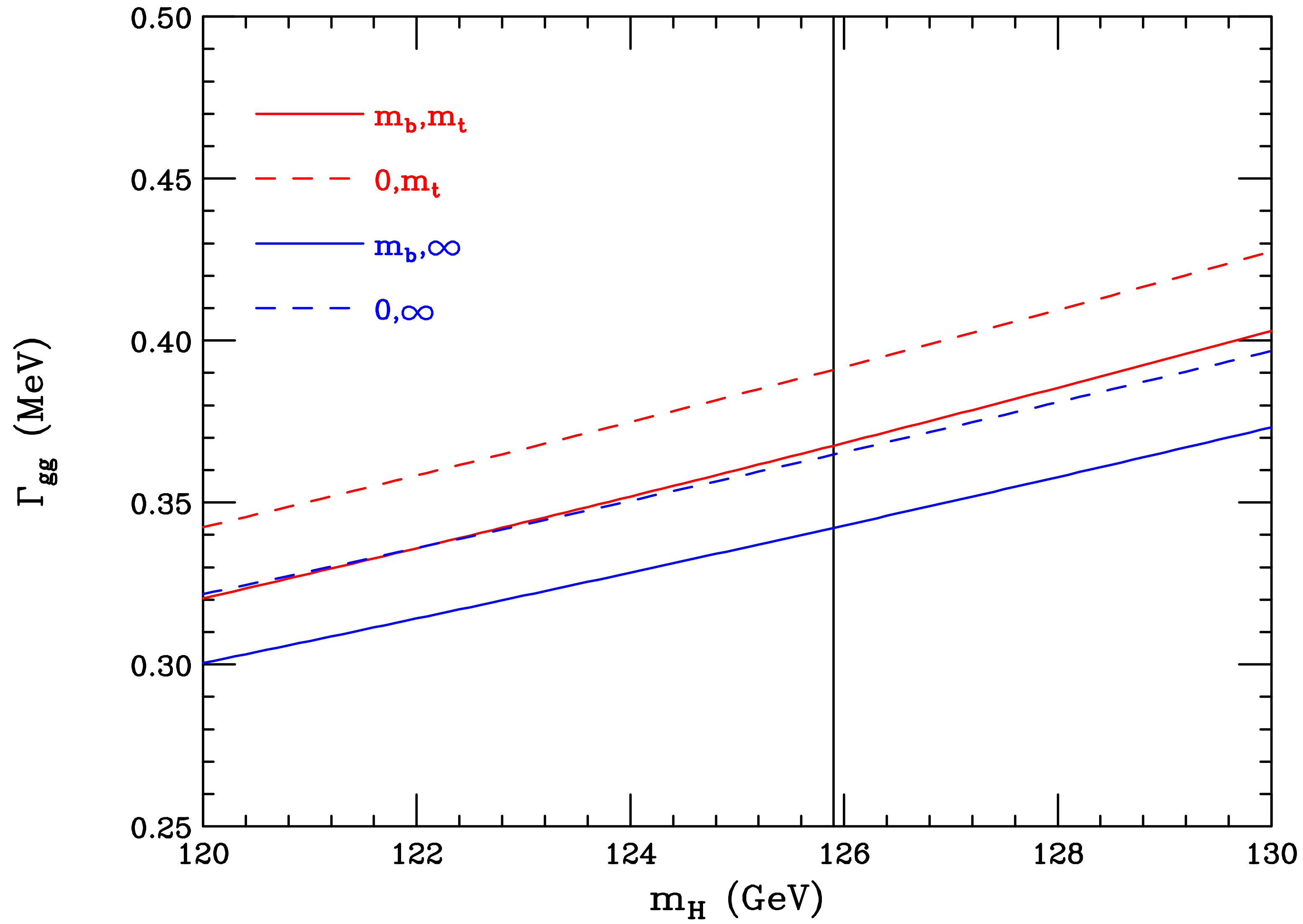
$m_t(\text{pole}) = 173.07 \pm 0.52(\text{stat}) \pm 0.72(\text{sys})$ GeV

→ $m_t(m_t) = 163.4 \pm 0.9$ GeV

$m_t(m_t) = 160^{+5}_{-4}$ GeV from cross section

Higgs→gg

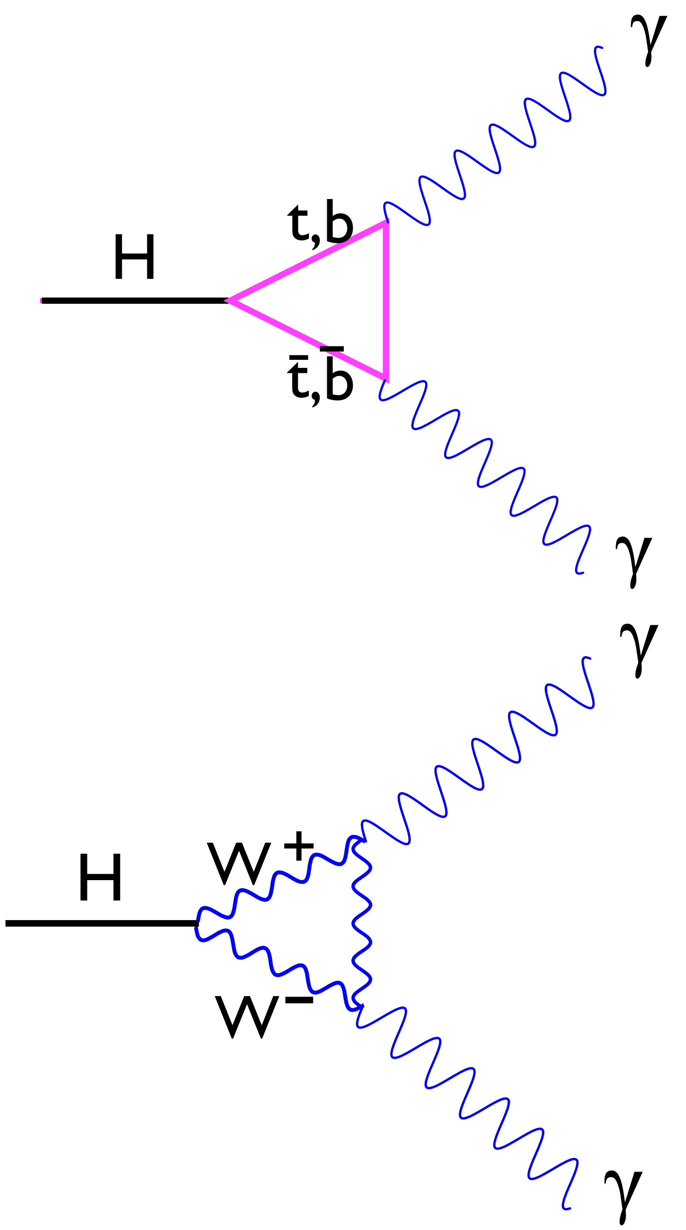


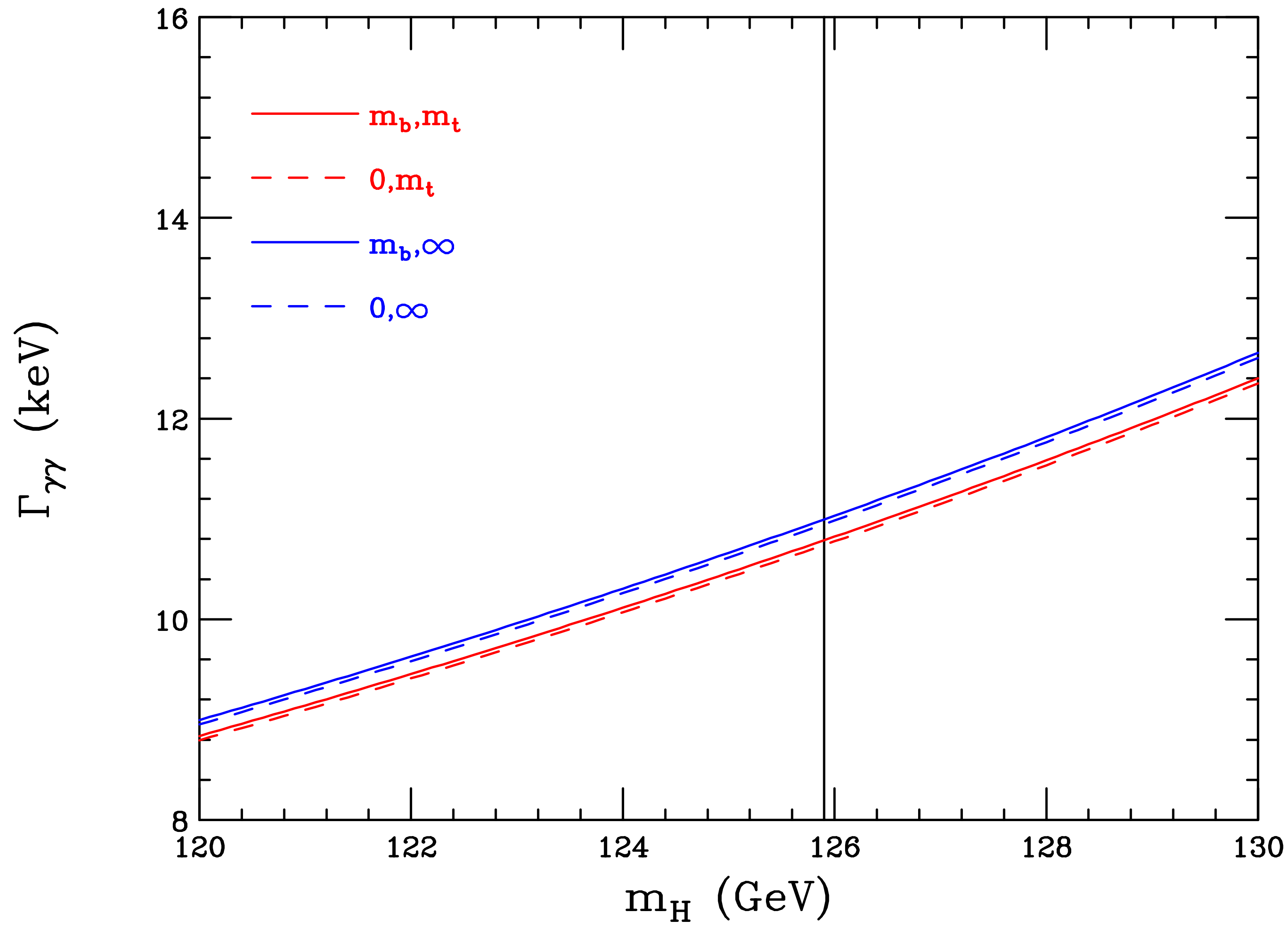


$$\Gamma_{gg} = \frac{\alpha_s^2 G_F M_H^3}{64\sqrt{2}\pi^3}\left|\sum_q I_q\left(\frac{m_q^2(M_H)}{M_H^2}\right)\right|^2 \left(1 + 6.14\,\alpha_s + 17.5\,\alpha_s^2 + 15.1\,\alpha_s^3 + \ldots\right)$$

- b contributes ~ -6%, which almost cancels top mass effect

Higgs→γγ





$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 G_F M_H^3}{128\sqrt{2}\pi^3}\left|3\sum_q e_q^2 I_q\left(\frac{m_q^2(M_H)}{M_H^2}\right) + I_W\left(\frac{M_W^2}{M_H^2}\right)\right|^2$$

- W loop dominates
- b contributes less, so top mass effect is significant (~-2%)

Higgs decay uncertainties: current

Almeida, Lee, Pokorski, Wells, 1311.6721v3

~ THU ??

	Parametric uncertainties %		Scale dependence
	added linearly	in quadrature	
	$P_\Gamma^\pm$(par.add.)	$P_\Gamma^\pm$(par.quad.)	$(P_\Gamma^+, P_\Gamma^-)(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

δM_H/MeV = 400(100) [ILC => 30]

Higgs mass

- ATLAS & CMS get masses differing by ~1 GeV from different channels and from each other:

ATLAS $\gamma\gamma$: $125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{sys})$

ATLAS ZZ*: $124.51 \pm 0.37(\text{stat}) \pm 0.06(\text{sys})$

CMS $\gamma\gamma$: $124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{sys})$

CMS ZZ*: $125.60 \pm 0.40(\text{stat}) \pm 0.20(\text{sys})$

- But their final numbers are more consistent:

ATLAS: $125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})$

CMS: $125.03 \,^{+0.26}_{-0.27}\,(\text{stat}) \,^{+0.13}_{-0.15}\,(\text{sys})$

- We need results from Run II !

Higgs decay uncertainties: prospects

Lepage, Mackenzie, Peskin, 1404.0319

	Parametric uncertainties %			$\delta_j = \delta\Gamma_j / 2\Gamma_j$ %		
	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

$\mathrm{PT} = \mathcal{O}(\alpha_s^4)$ [current $= \mathcal{O}(\alpha_s^3)$]

$\mathrm{LS} = 0.030\,\mathrm{fm}$ [current $= 0.045\,\mathrm{fm}$]

$\mathrm{LS}^2 = 0.023\,\mathrm{fm}$ [computing × 100]

ST = statistics × 100

Conclusions on Higgs Decays

- Higgs partial widths currently predicted to 2%-5%
- Higgs mass uncertainty important for VV* modes (at LHC, not ILC)
- Predictions to 1%-2% look feasible, with big investments in perturbative and lattice QCD
- Is this good enough??

Monte Carlo Event Generation

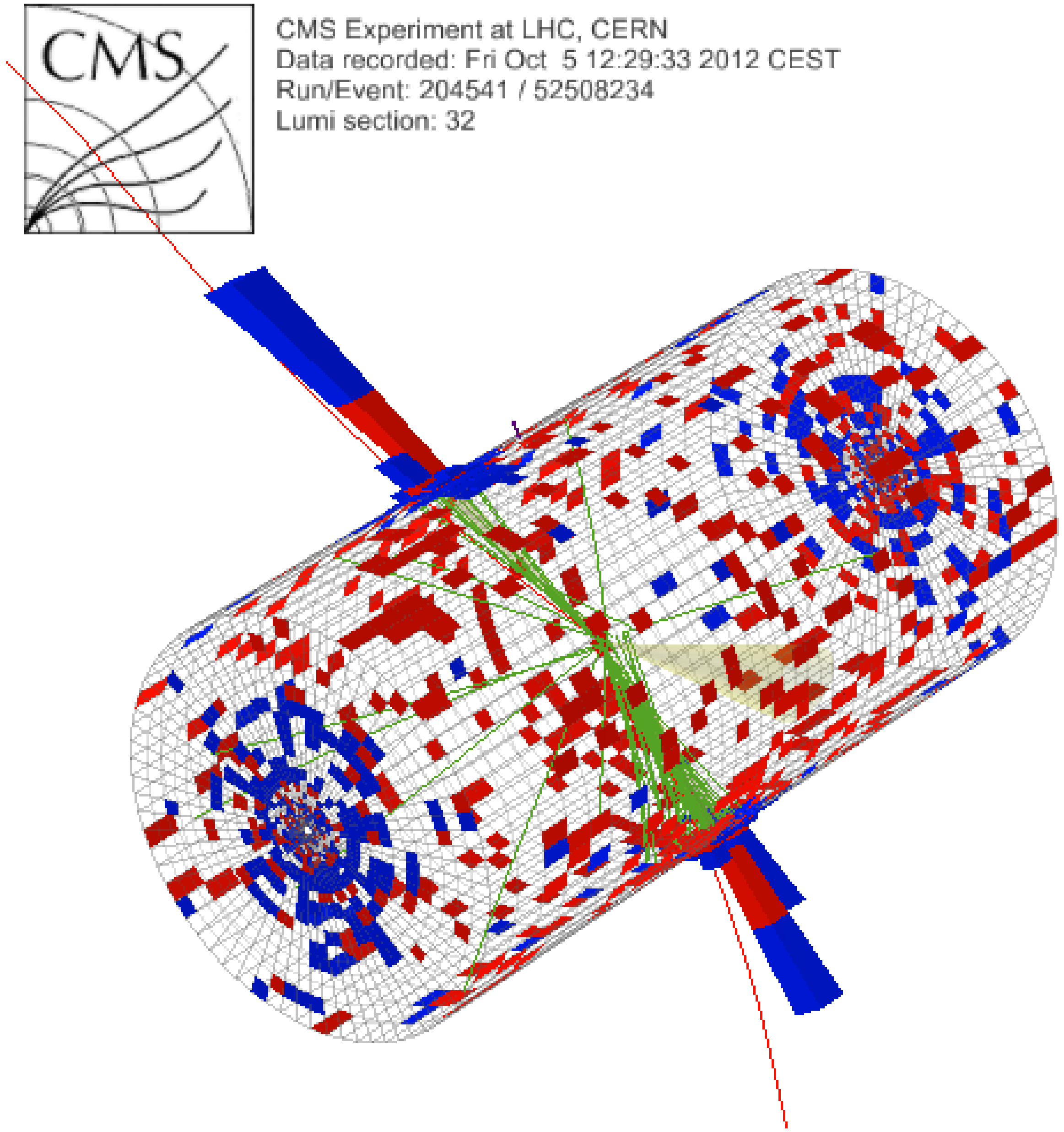
Monte Carlo Event Generation

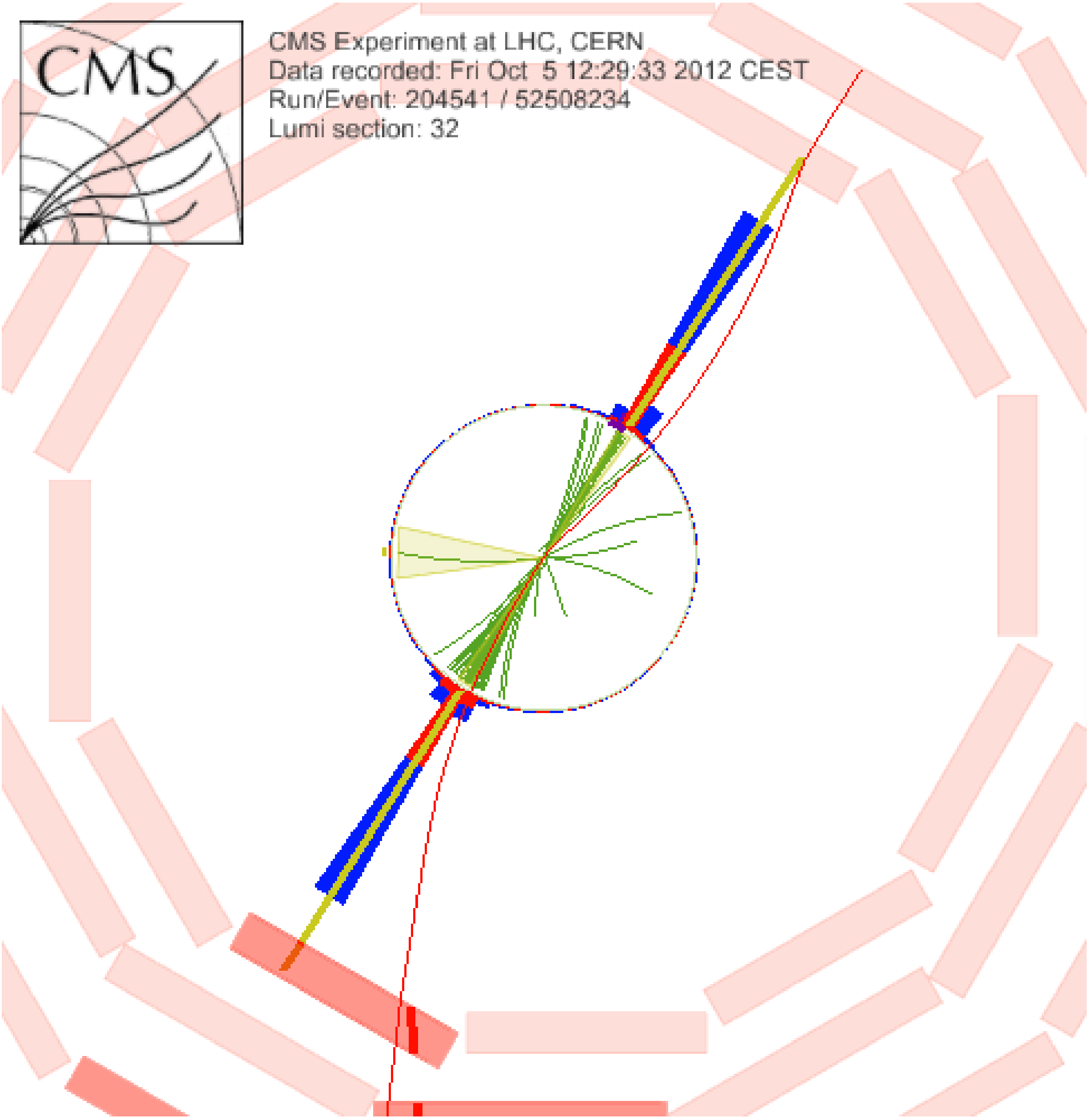
- Monte Carlo event generation:
    - theoretical status and limitations
- Recent improvements:
    - perturbative and non-perturbative
- Overview of results:
    - W, Z, top, Higgs, BSM (+jets)

Monte Carlo Event Generation

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

A high-mass dijet event

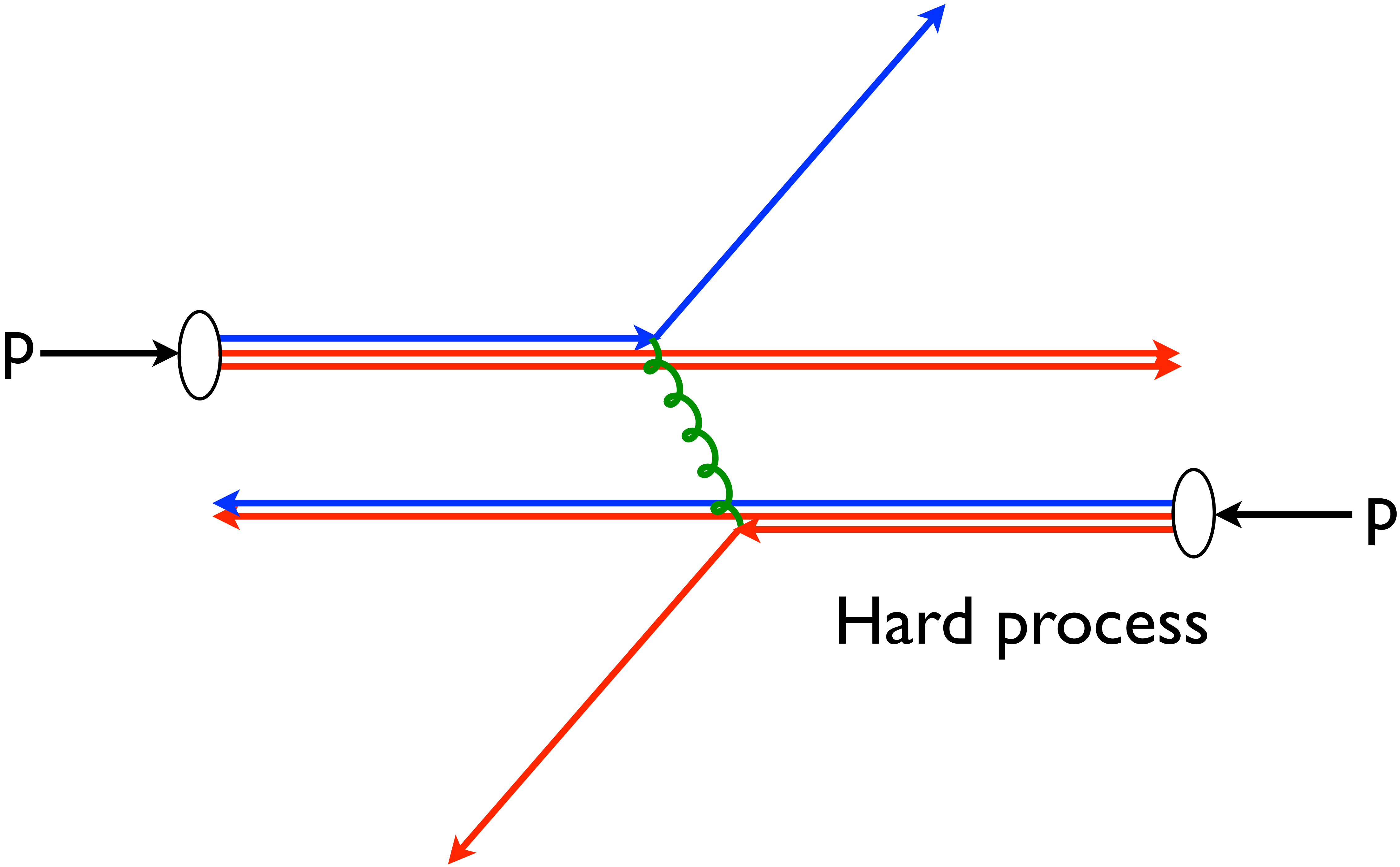




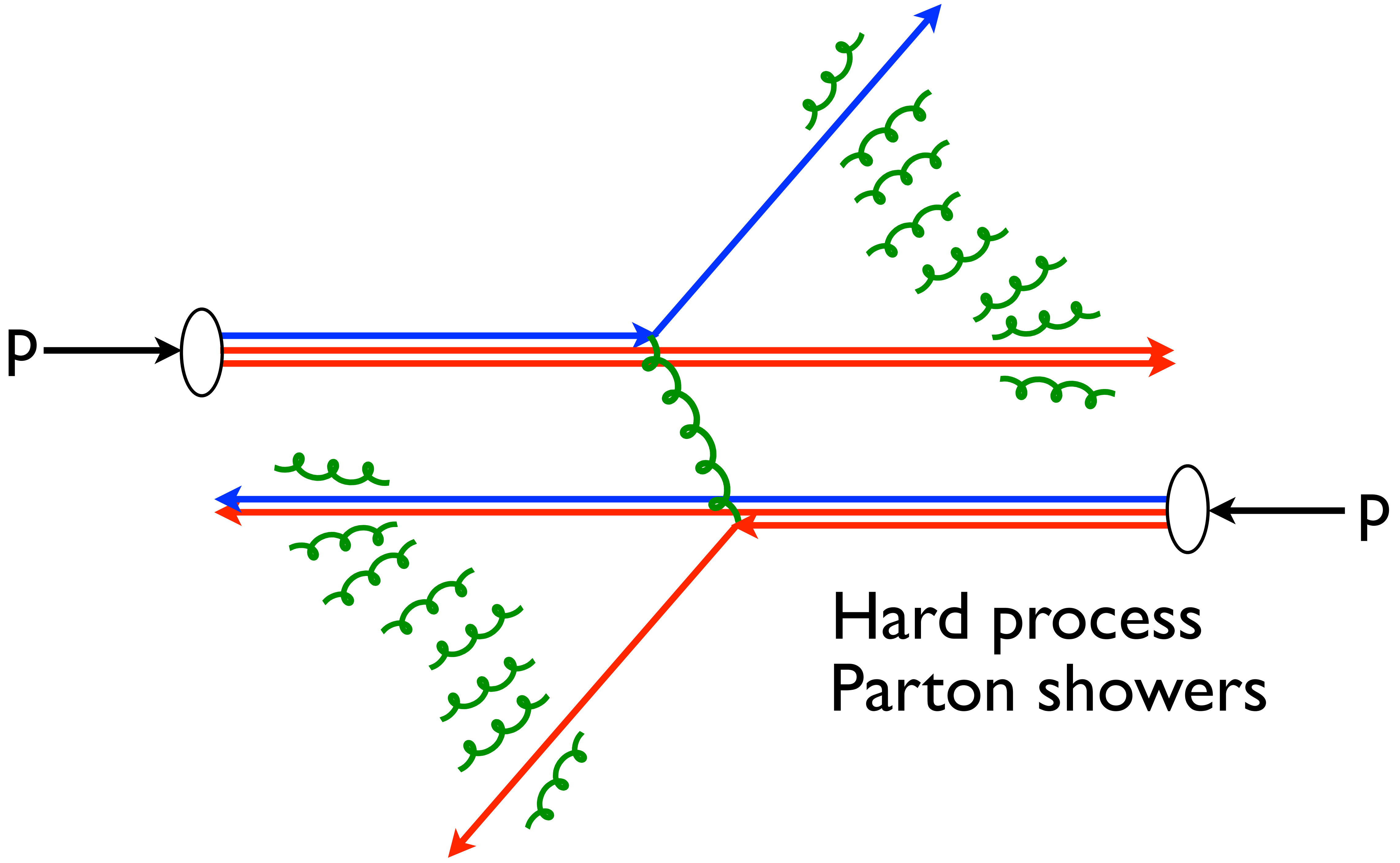
- M_{jj} = 5.15 TeV

CMS PAS EXO-12-059

Event Generation

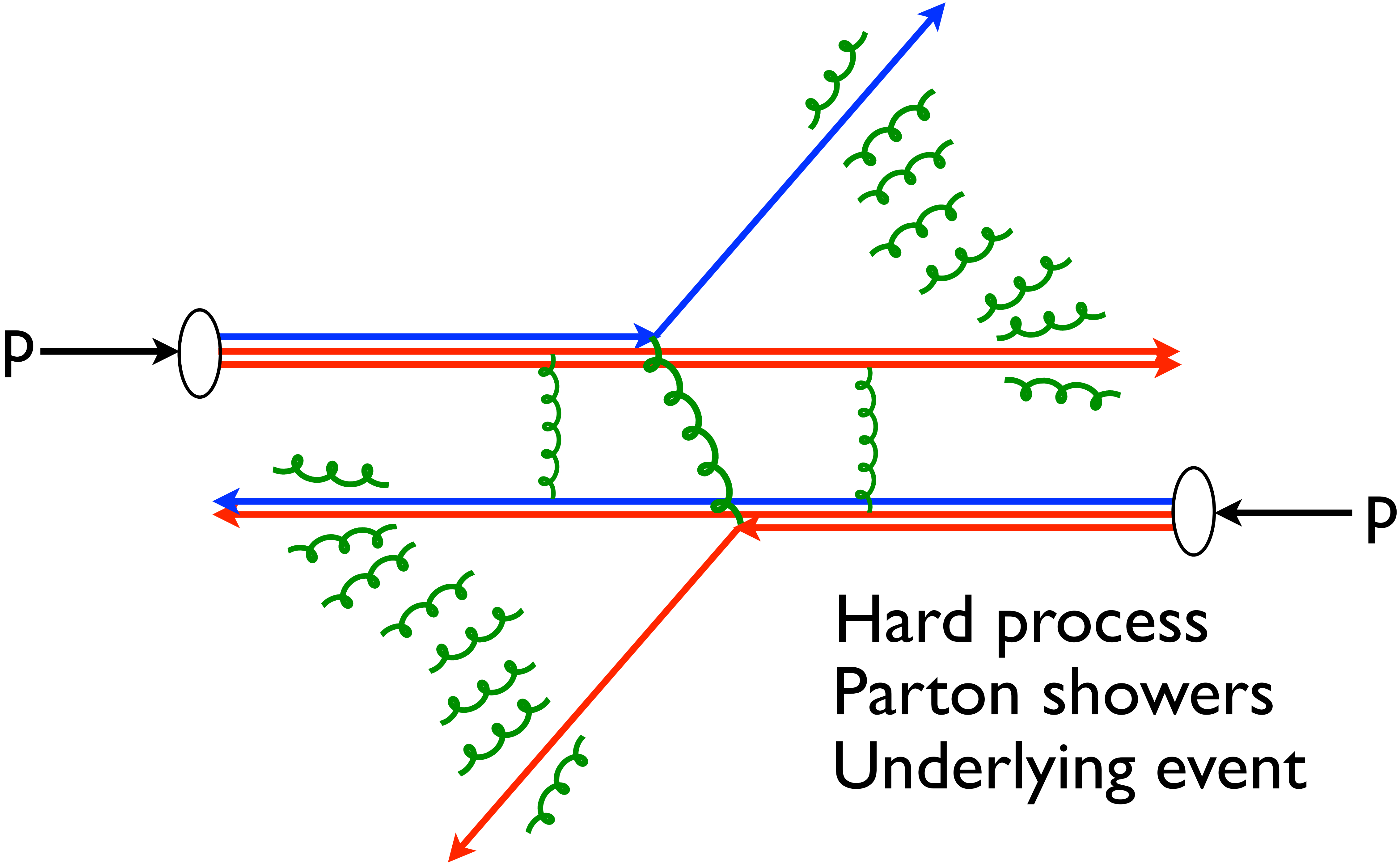


Event Generation



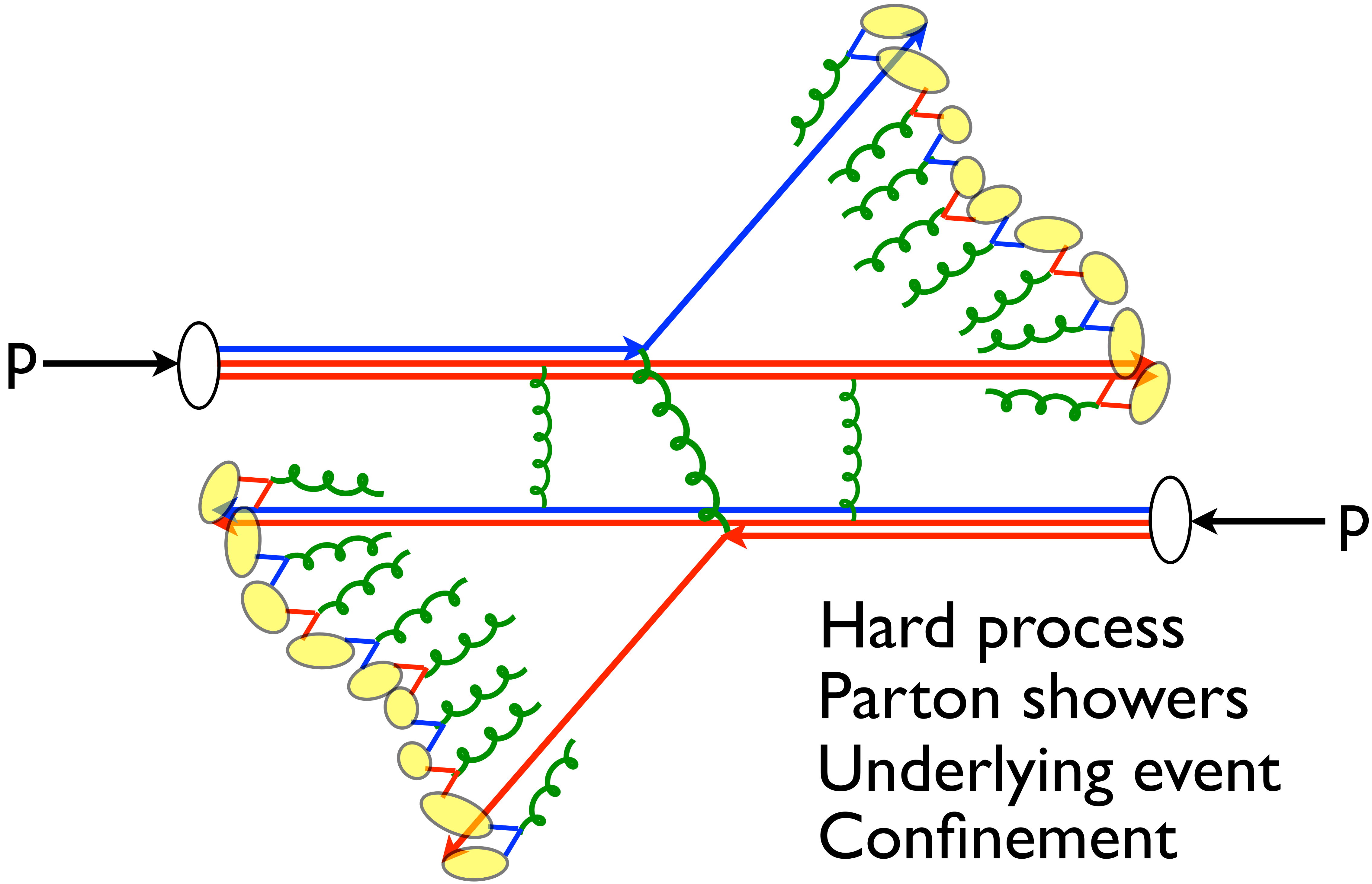
Hard process
Parton showers

Event Generation



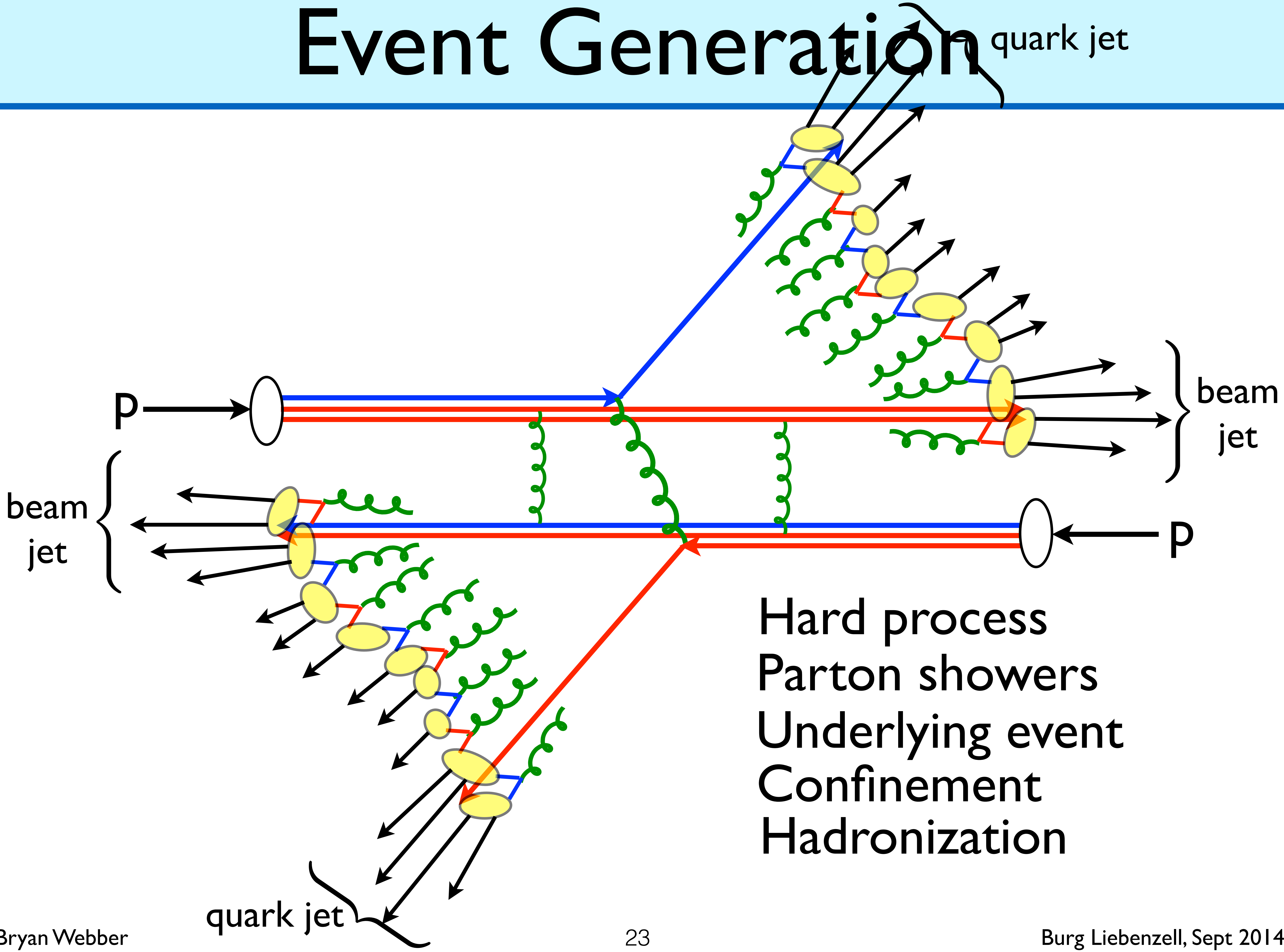
Hard process
Parton showers
Underlying event

Event Generation



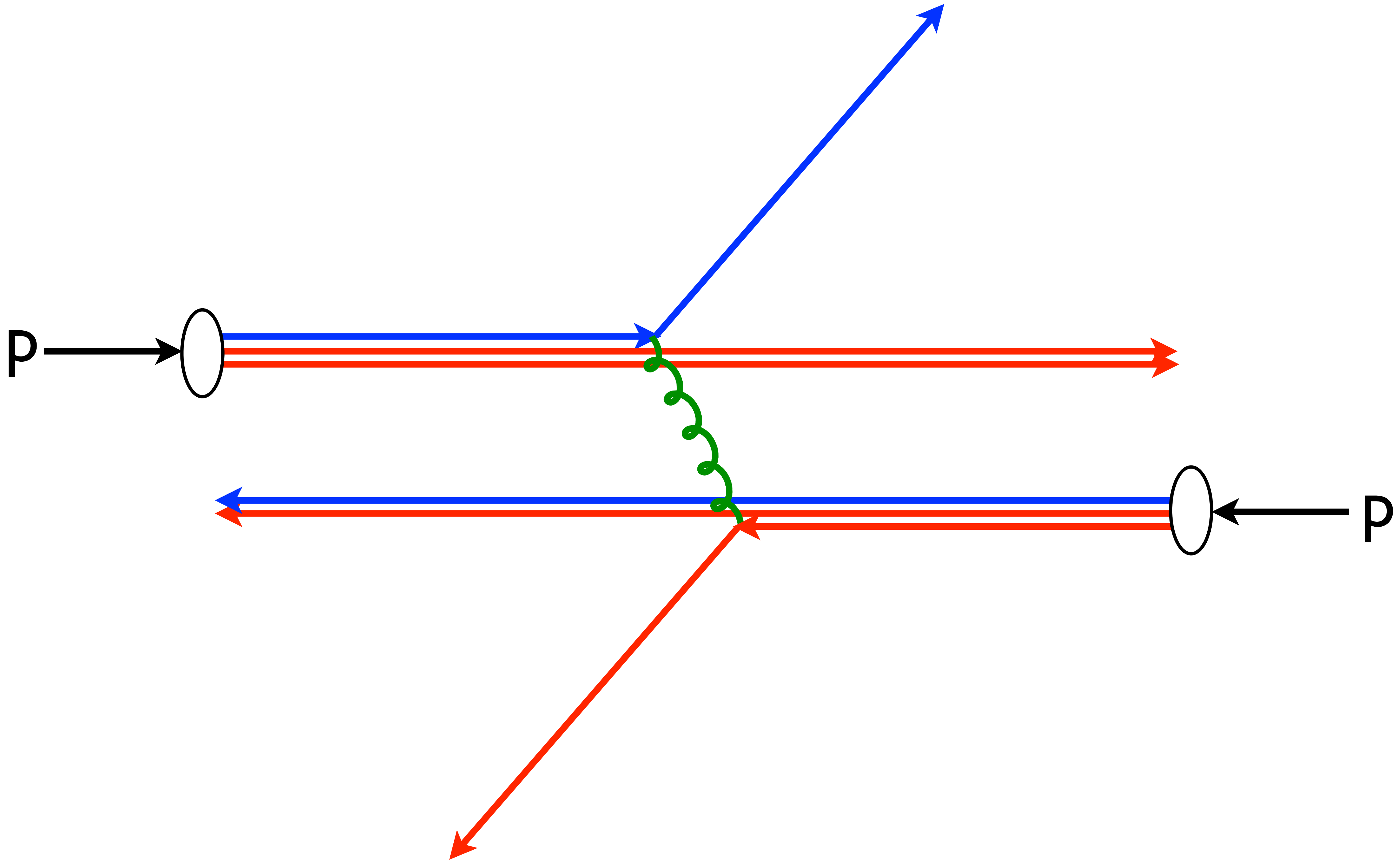
Hard process
Parton showers
Underlying event
Confinement

Event Generation



Hard process
Parton showers
Underlying event
Confinement
Hadronization

Theoretical Status



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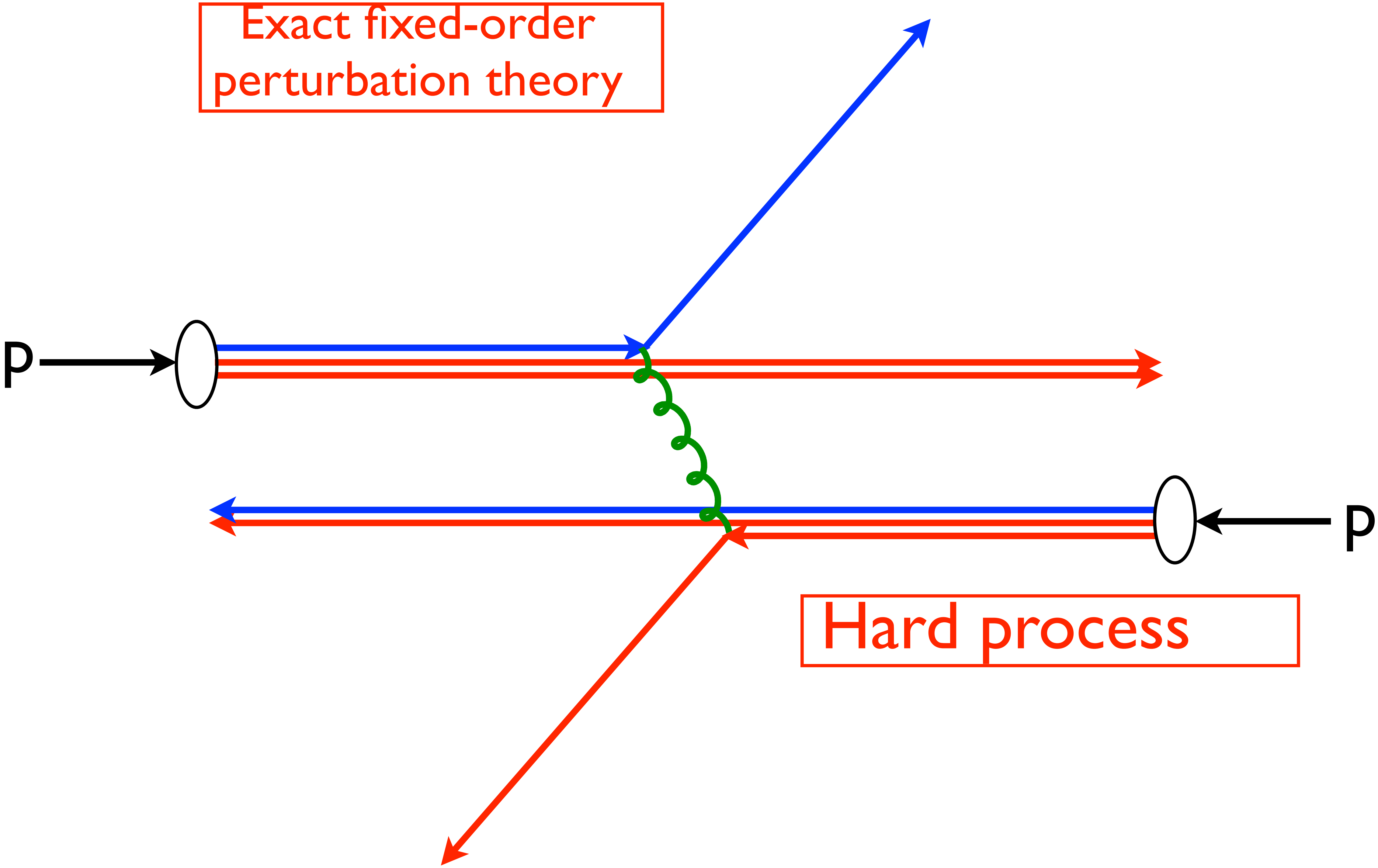

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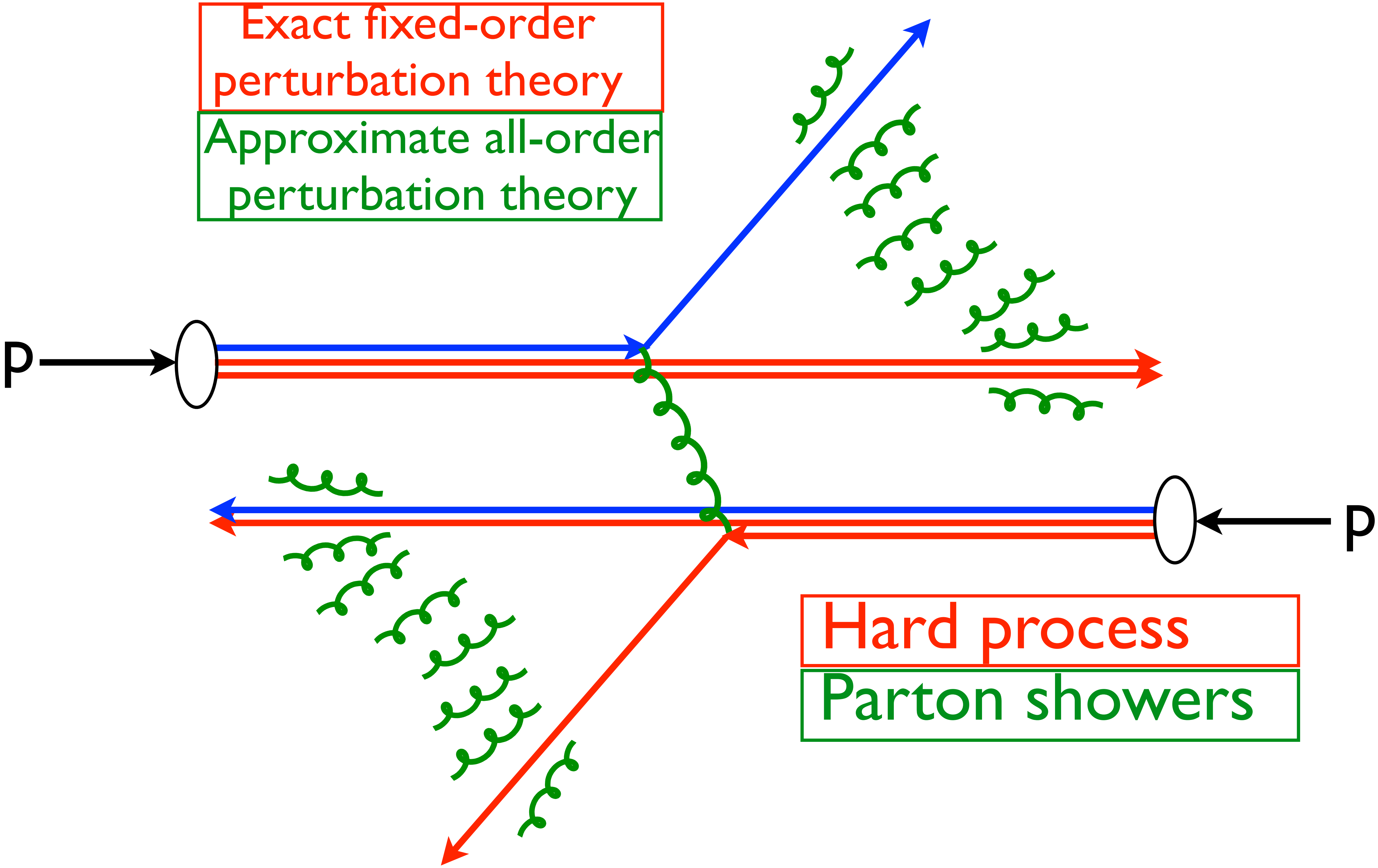

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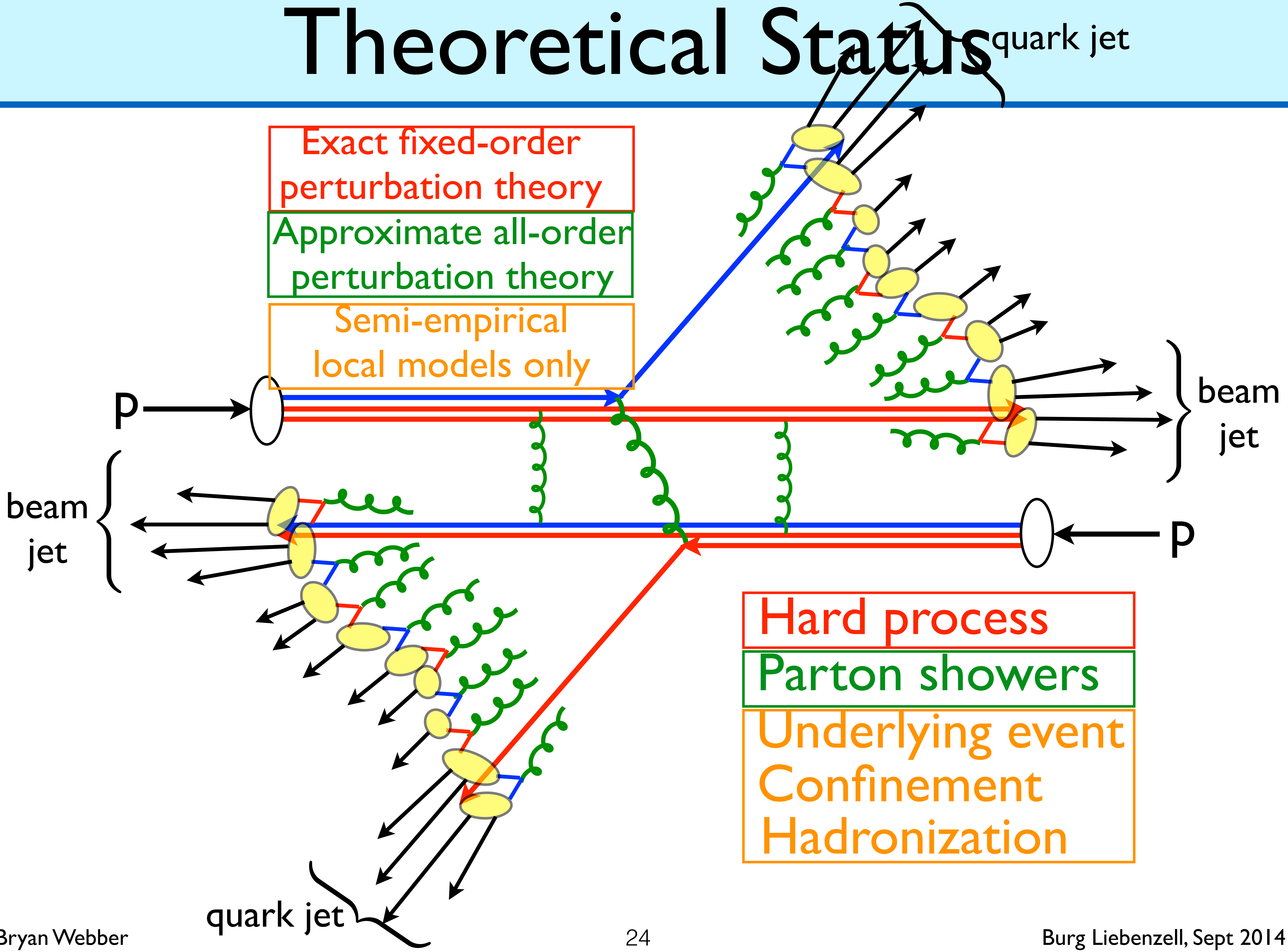


Exact fixed-order perturbation theory

Approximate all-order perturbation theory

Semi-empirical local models only

Hard process

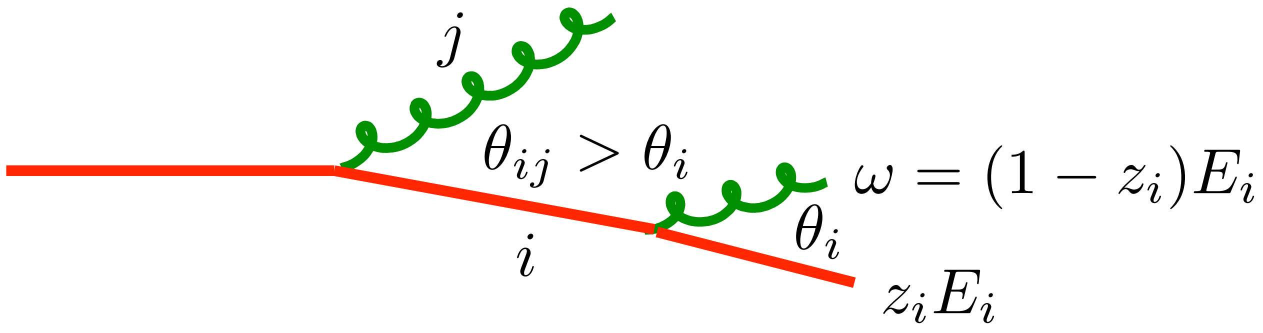
Parton showers

Underlying event
Confinement
Hadronization

Parton Shower Approximation

- Keep only most singular parts of QCD matrix elements:
- Collinear $d\sigma_{n+1} \approx \frac{\alpha_S}{2\pi}\sum_i P_{ii}(z_i,\phi_i)\,dz_i \frac{d\xi_i}{\xi_i}\frac{d\phi_i}{2\pi} d\sigma_n$ $\qquad \xi_i = 1-\cos\theta_i$
- Soft

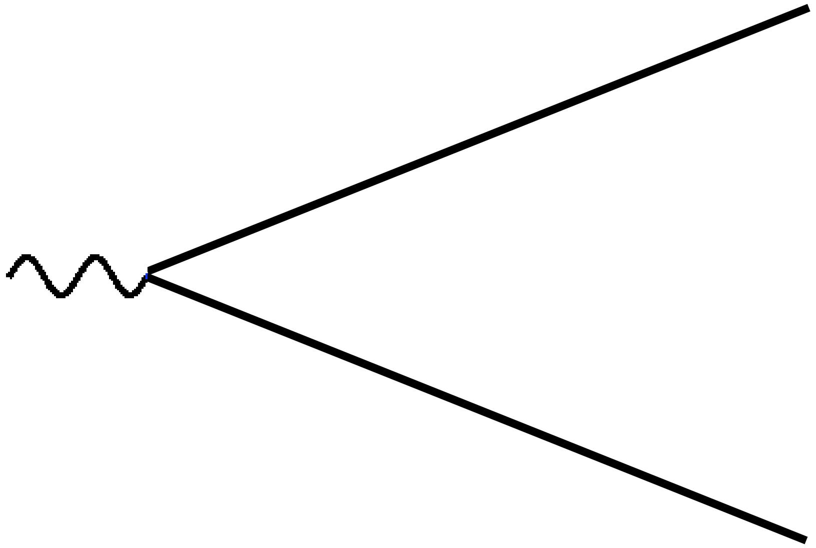
$$\begin{aligned} d\sigma_{n+1} &\approx \frac{\alpha_S}{2\pi}\sum_{i,j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\frac{p_i\cdot p_j}{p_i\cdot k\, p_j\cdot k}\omega\, d\omega\, d\xi_i \frac{d\phi_i}{2\pi} d\sigma_n \\ &= \frac{\alpha_S}{2\pi}\sum_{i,j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\frac{\xi_{ij}}{\xi_i\,\xi_j}\frac{d\omega}{\omega} d\xi_i \frac{d\phi_i}{2\pi} d\sigma_n \\ &\approx \frac{\alpha_S}{2\pi}\sum_{i,j}(-\mathbf{T}_i\cdot\mathbf{T}_j)\,\Theta(\xi_{ij}-\xi_i)\frac{d\omega}{\omega}\frac{d\xi_i}{\xi_i} d\sigma_n \end{aligned}$$



→ Angular-ordered parton shower (or dipoles)

Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale Q towards lower values
- At a scale near Λ_{QCD}~200 MeV, perturbation theory breaks down and hadrons are formed
- Before that, at scales Q_0 ~ few x Λ_{QCD}, there is universal preconfinement of colour
- Colour, flavour and momentum flows are only locally redistributed by hadronization



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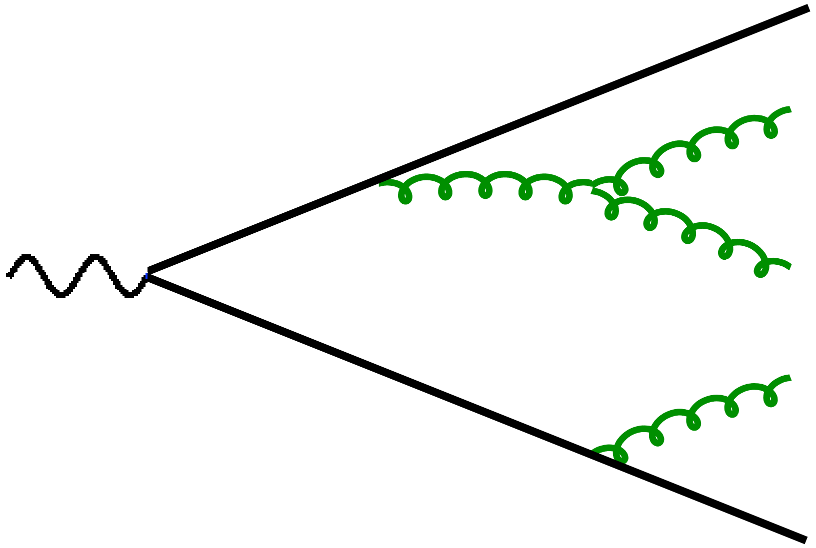

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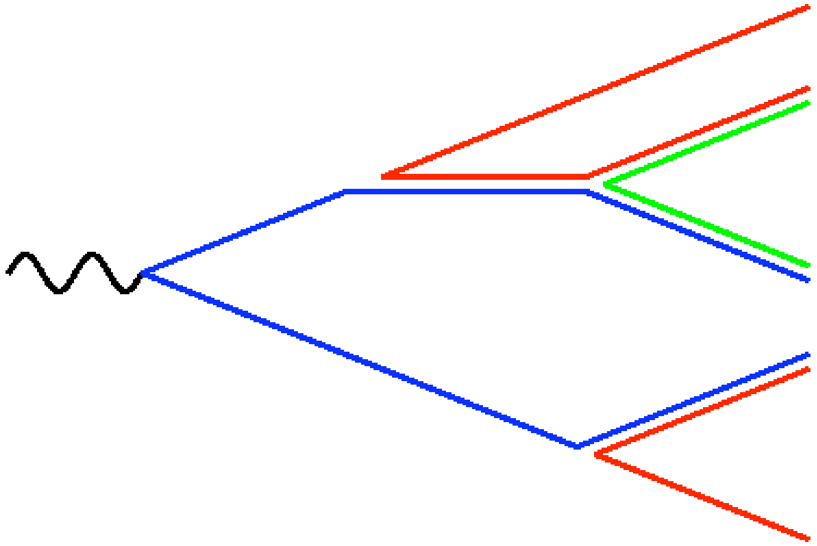

String Hadronization Model

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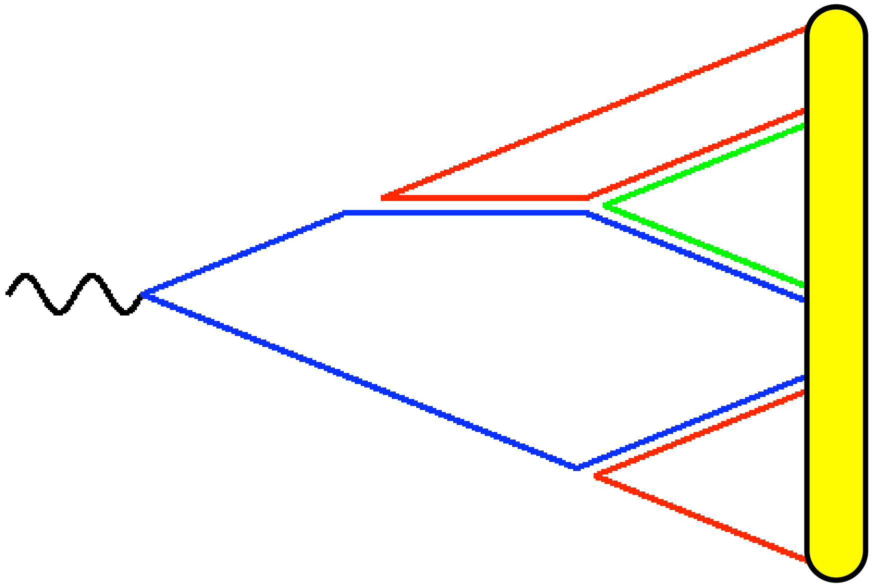
- Colour flow dictates how to connect hadronic string (width ~ few x Λ_{QCD}) with shower



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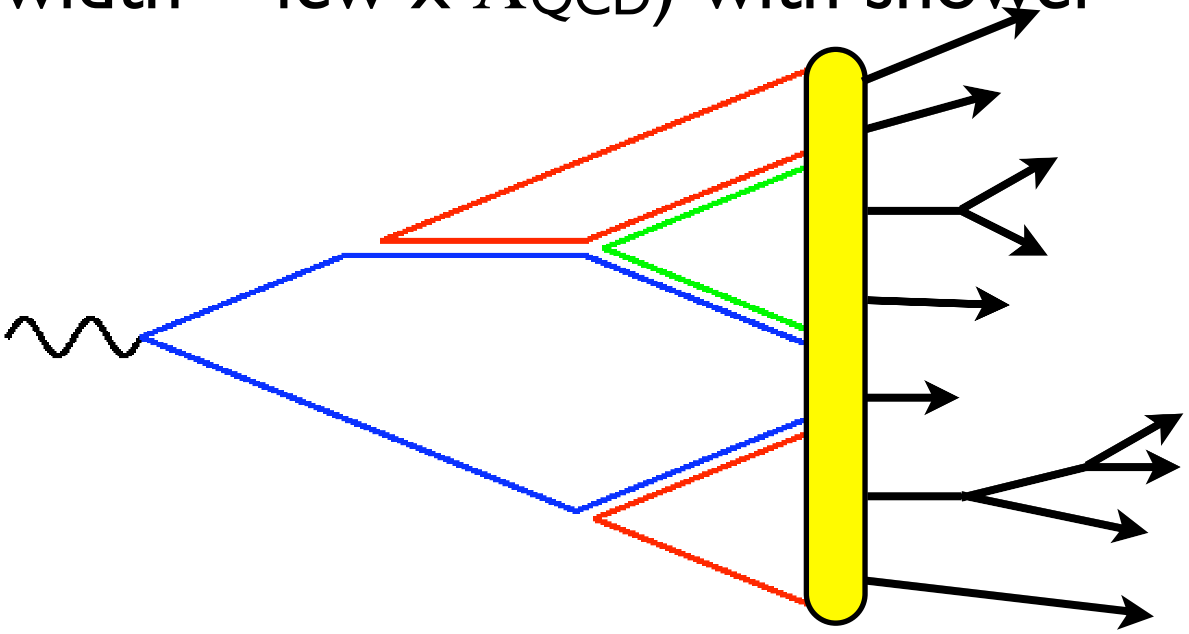

Cluster Hadronization Model

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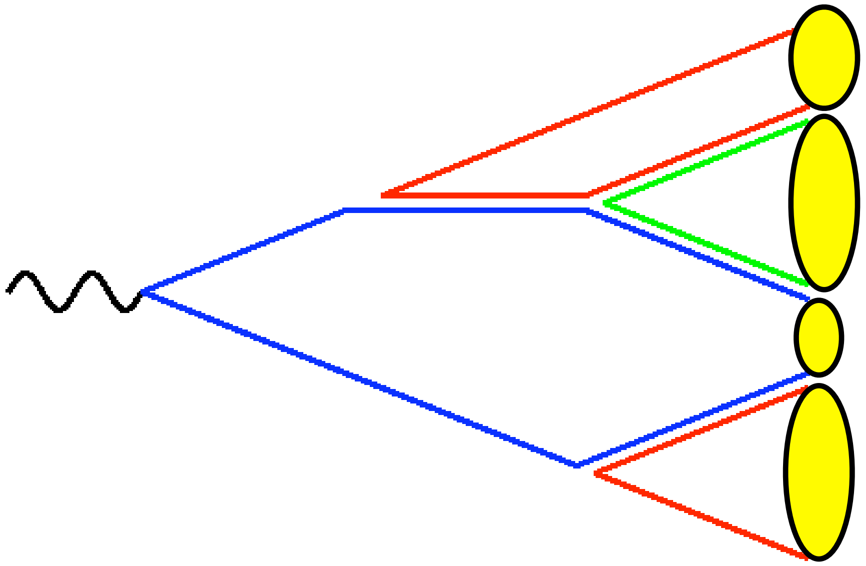
- At a scale near Λ_{QCD}~200 MeV, perturbation theory breaks down and hadrons are formed
- Before that, at scales Q_0 ~ few x Λ_{QCD}, there is universal preconfinement of colour
- Decay of preconfined clusters provides a direct basis for hadronization



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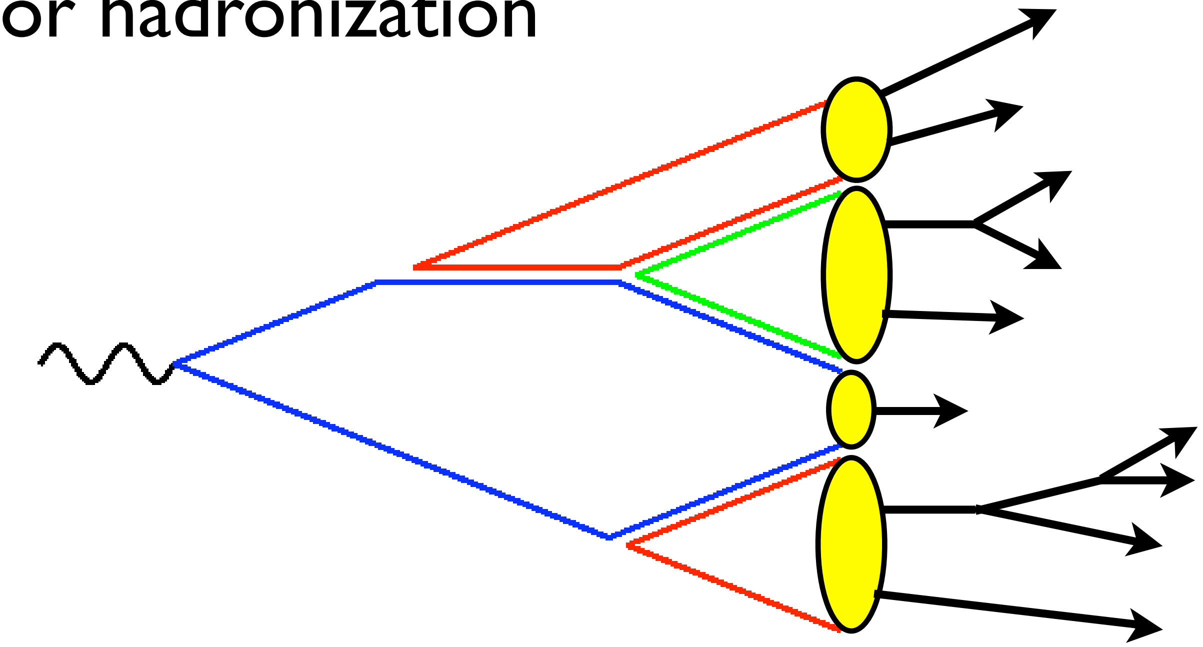
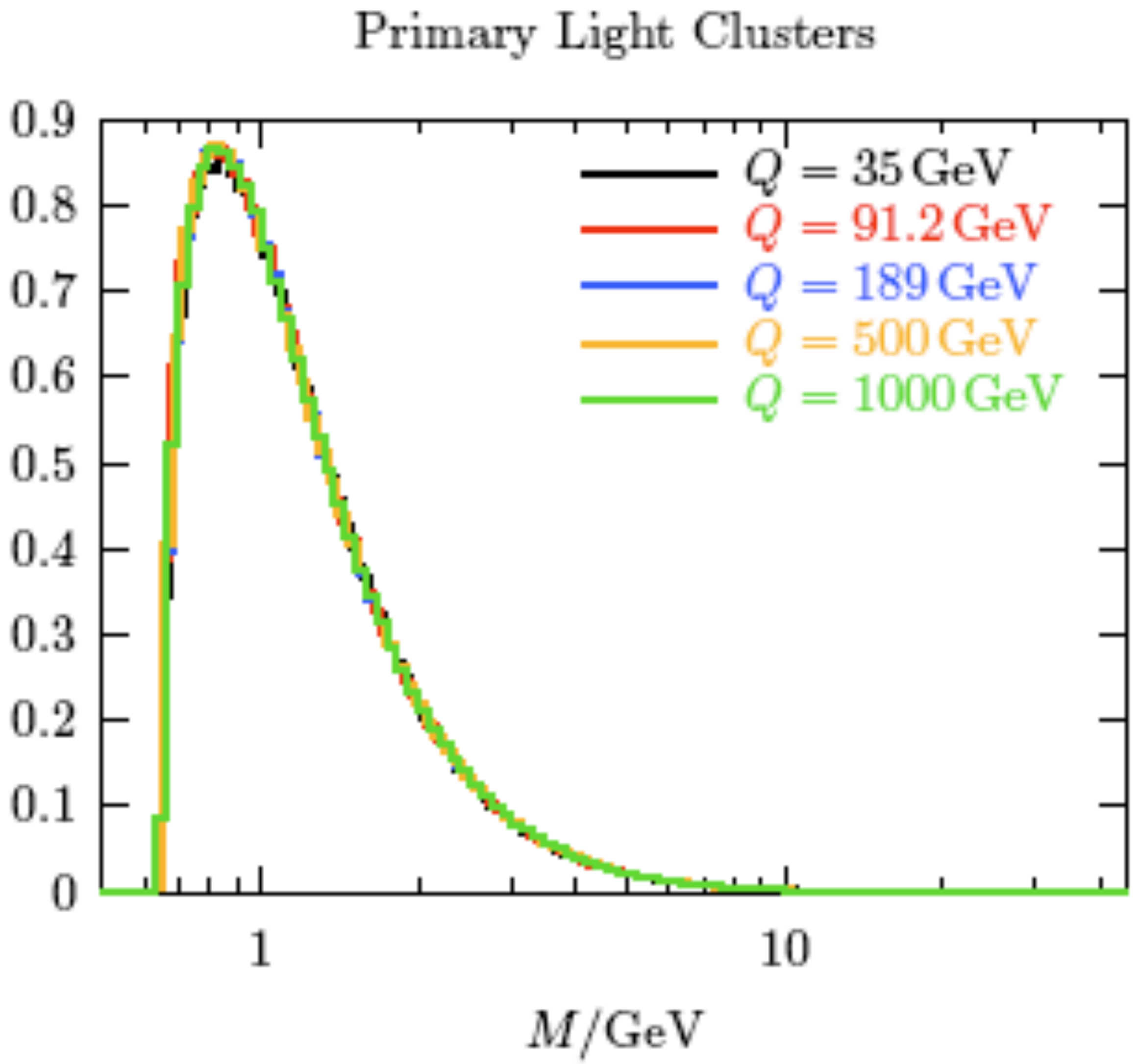


Colour Preconfinement

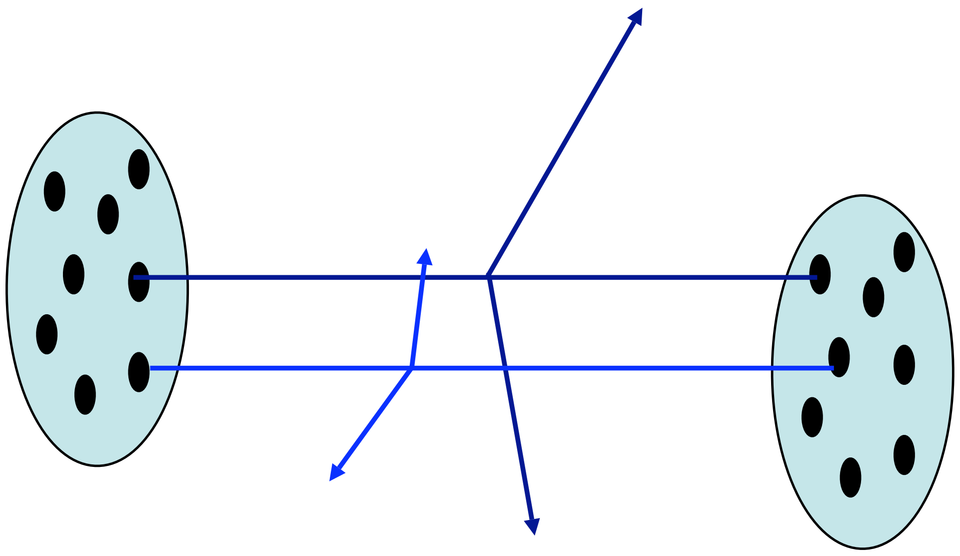


- Mass distribution of preconfined clusters is universal
- Phase-space decay model for most clusters
- High-mass tail decays anisotropically (string-like)

Hadronization Status

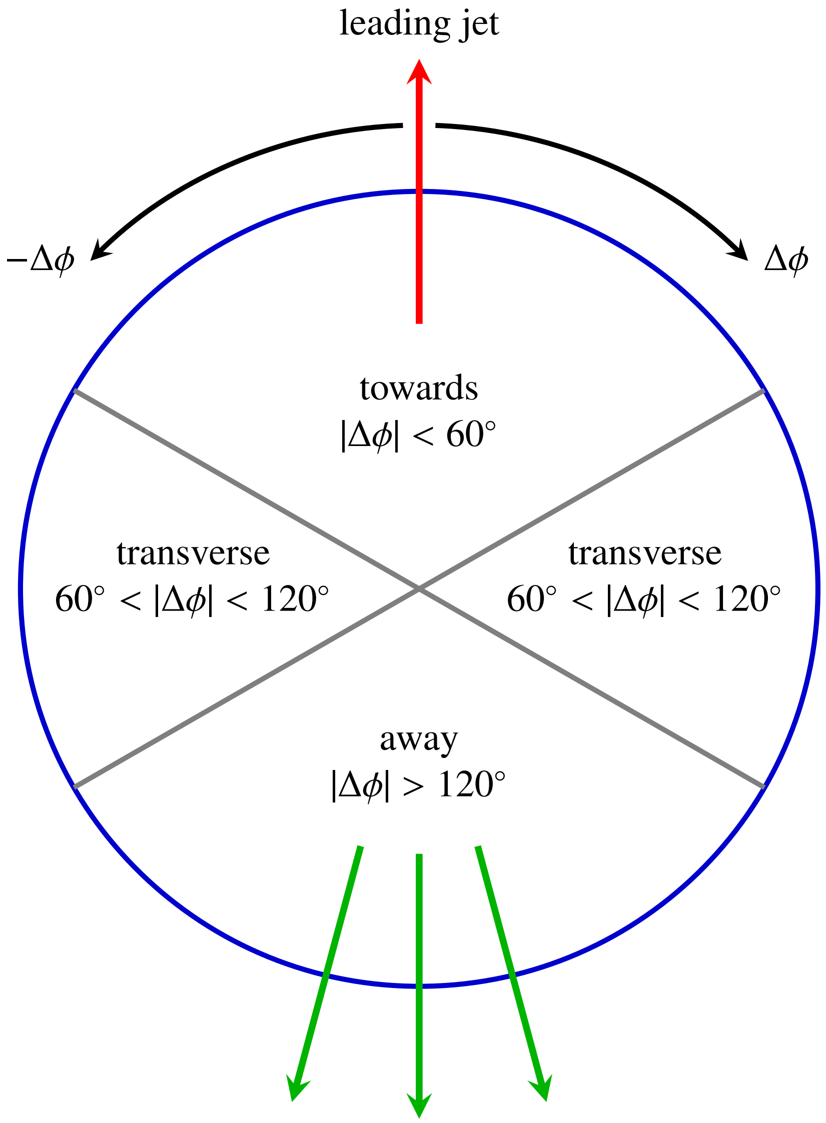
- No fundamental progress since 1980s
  - Available non-perturbative methods (lattice, AdS/QCD, ...) are inapplicable
- Less important in some respects in LHC era
  - Jets, leptons and photons are observed objects, not hadrons
- But still important for detector effects
  - Jet response, heavy-flavour tagging, lepton and photon isolation, ...

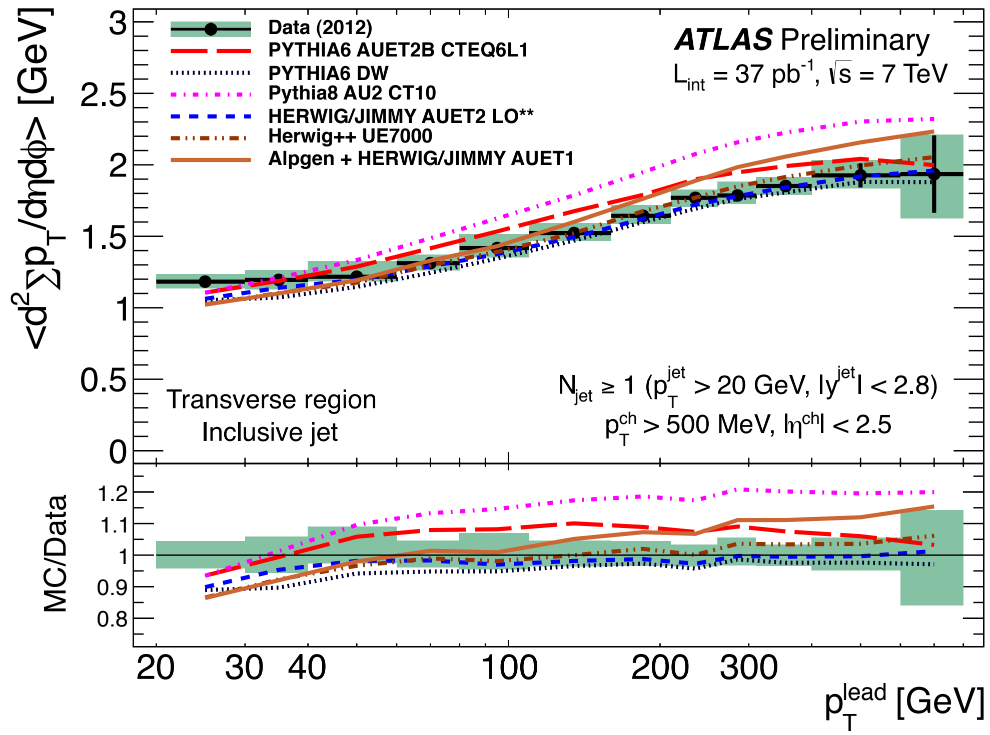
Underlying Event

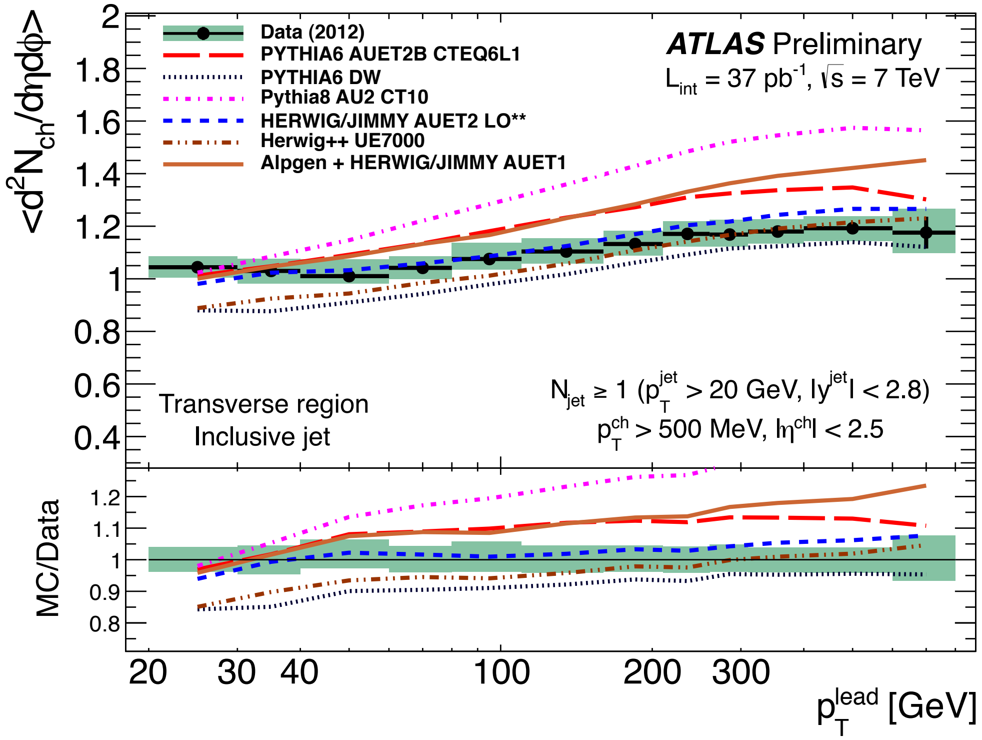


- Multiple parton interactions in same collision
  - Depends on density profile of proton
- Assume QCD 2-to-2 secondary collisions
  - Need cutoff at low p_T
- Need to model colour flow
  - Colour reconnections are necessary

Underlying Event

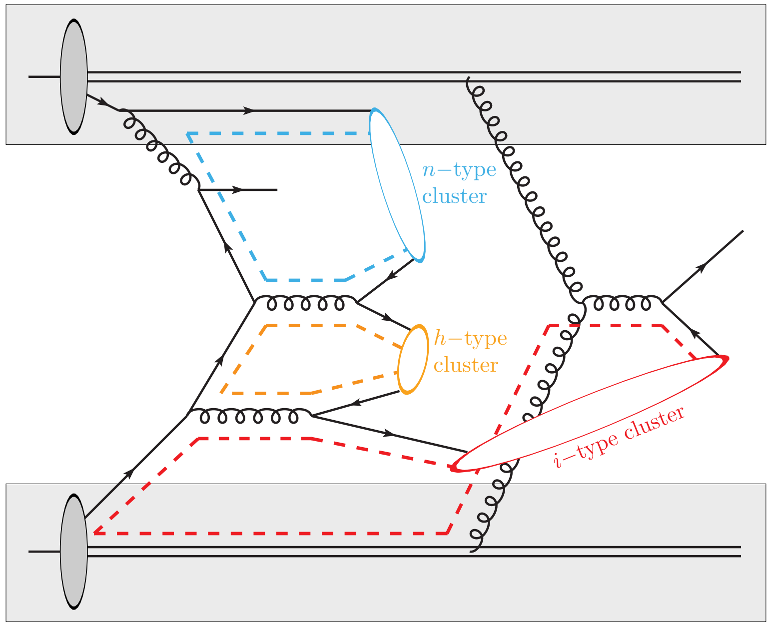


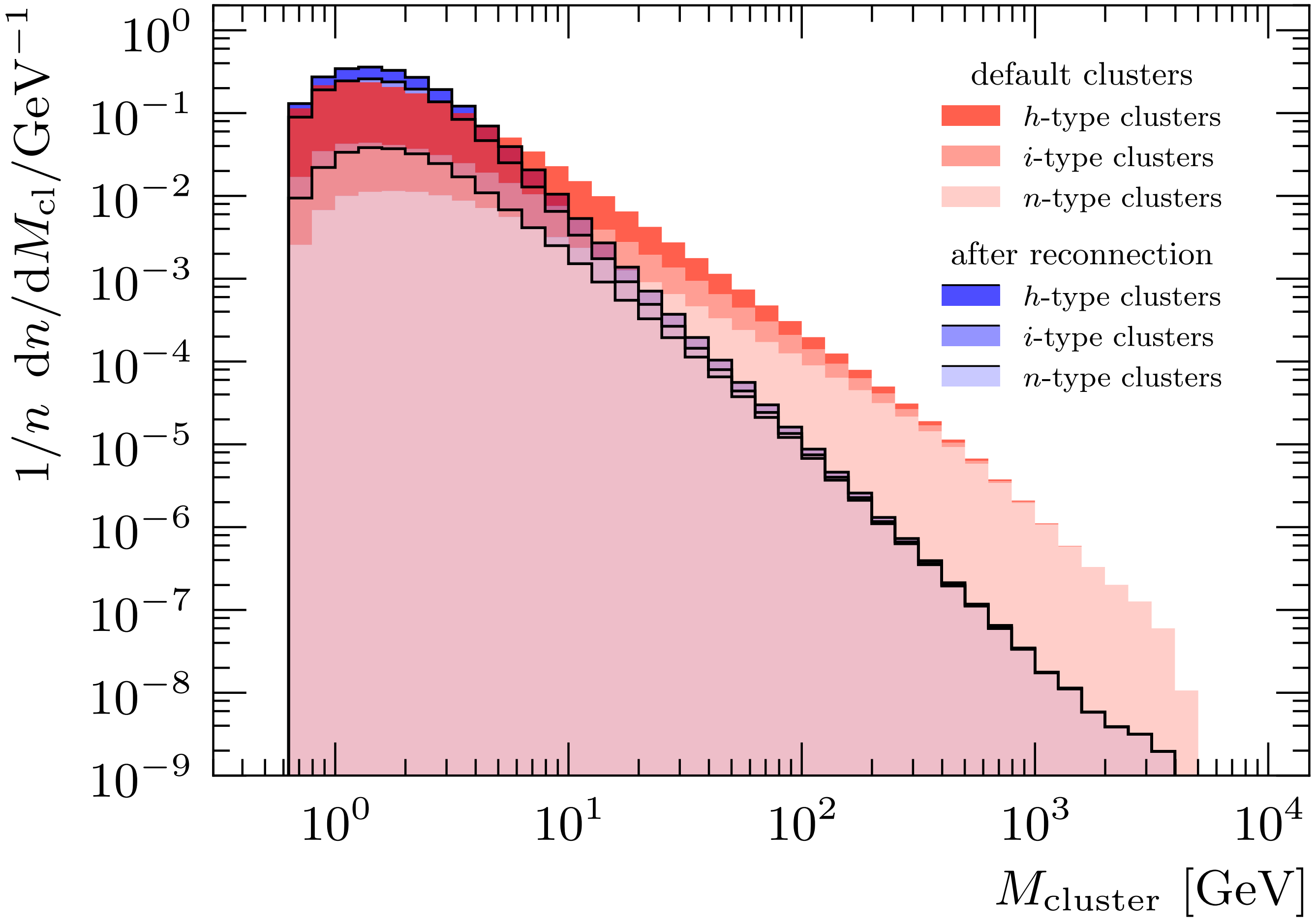


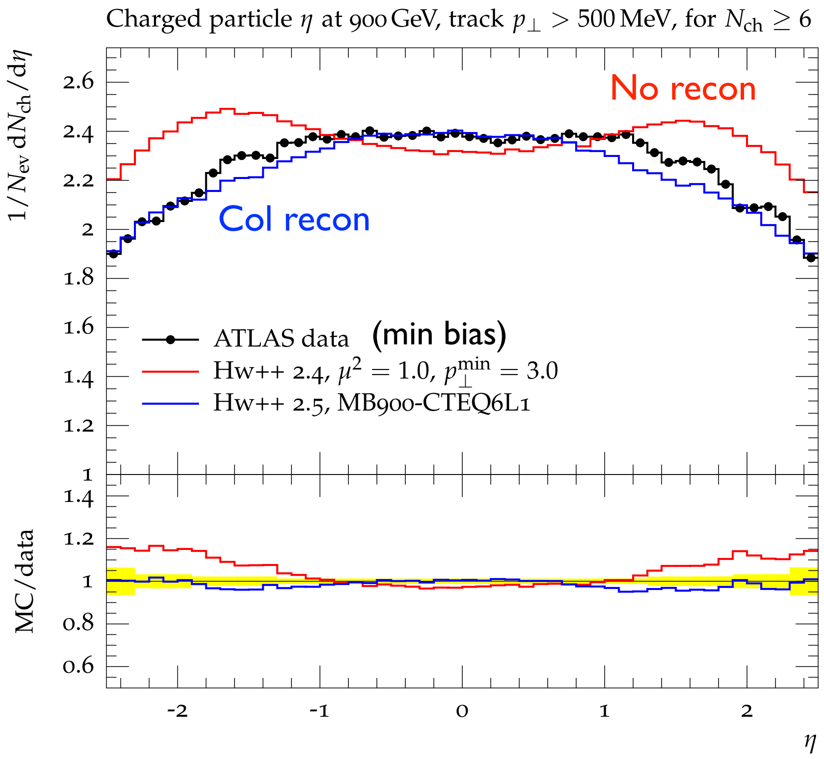


ATLAS CONF-2012-164

Colour Reconnection



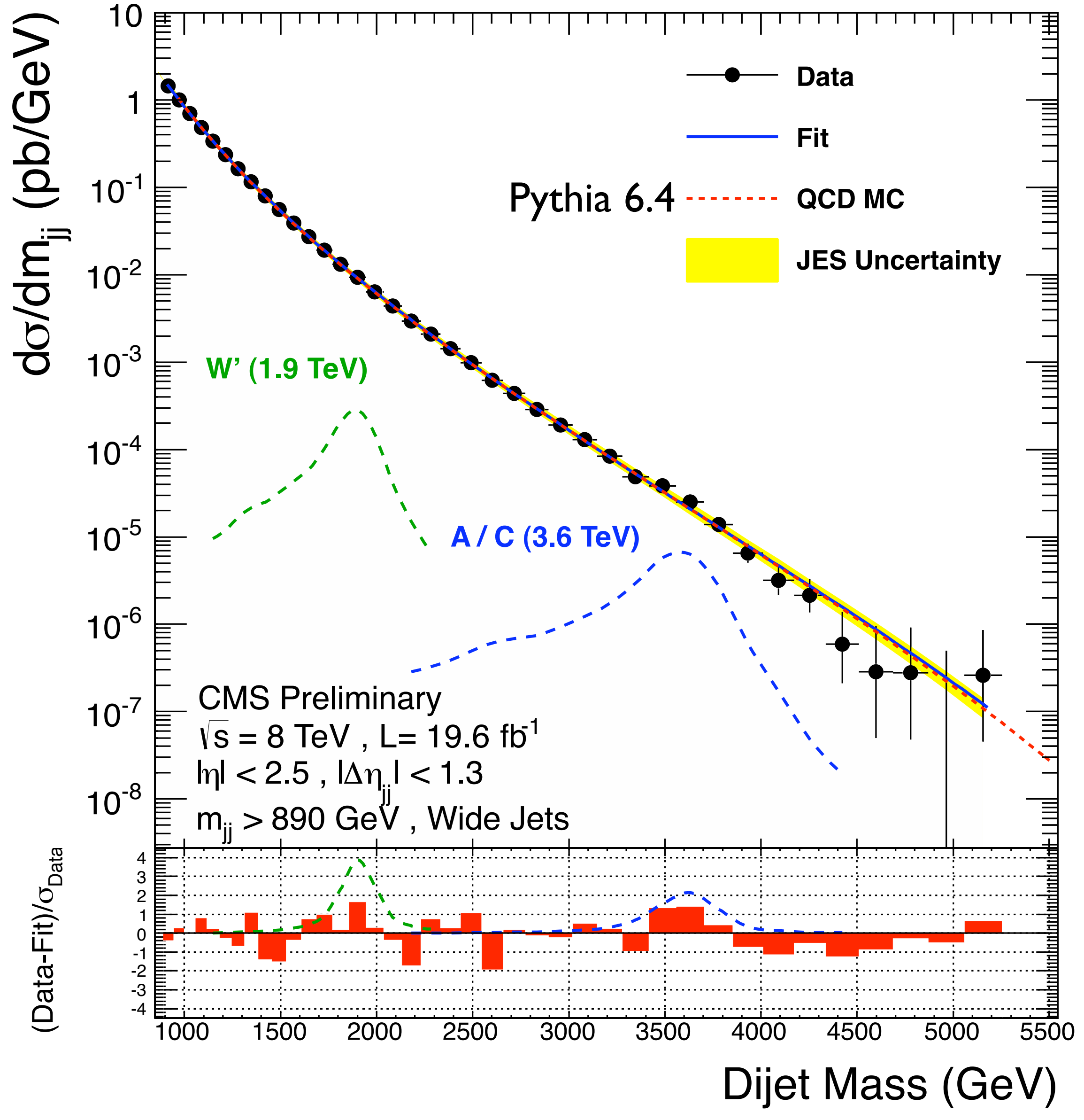


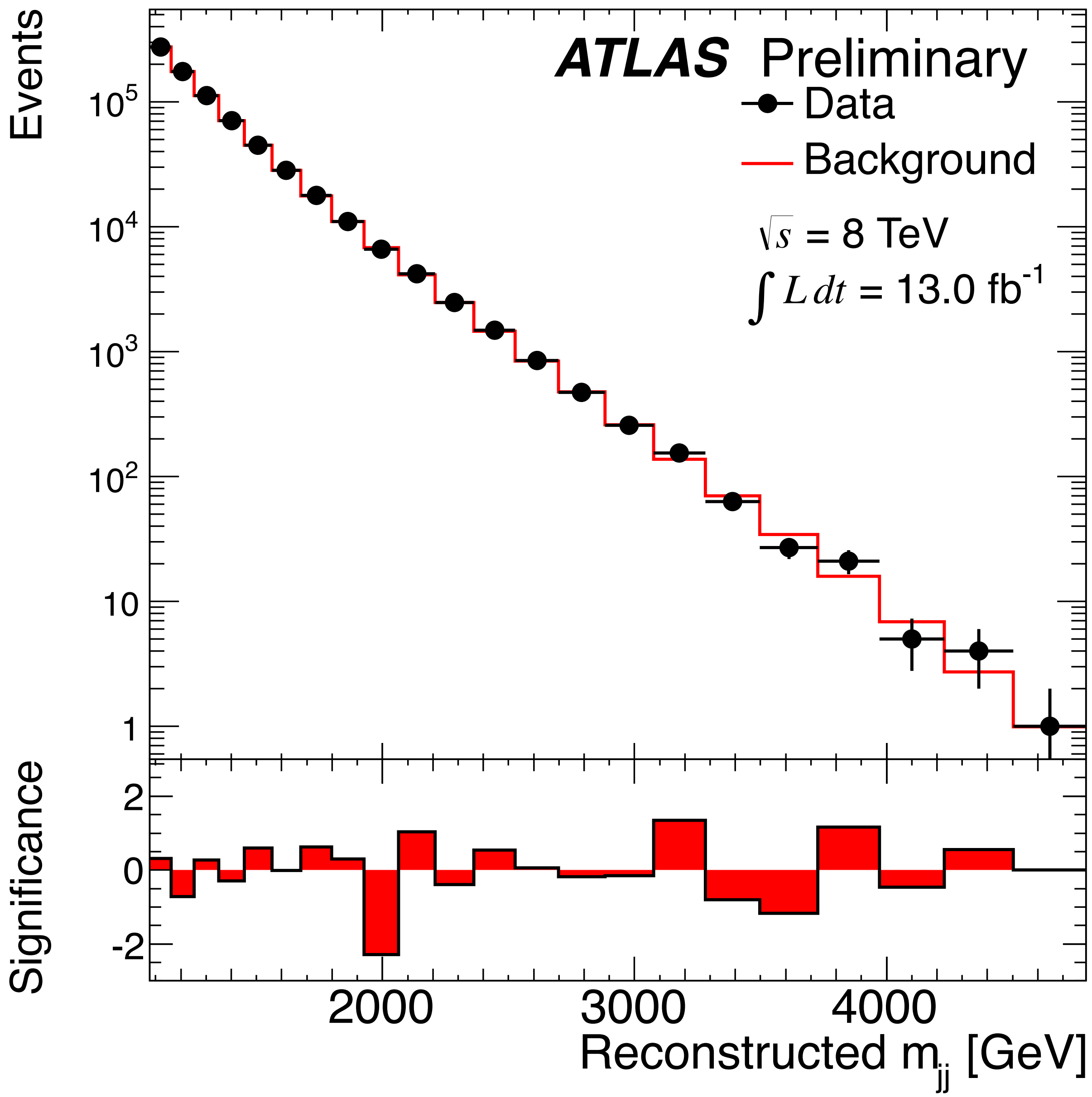


- “Colour length” $\lambda \equiv \sum_{i=1}^{N_{\mathrm{cl}}} m_i^2$ reduced by reconnection
- Massive leading clusters reduced
- Similar need in string model

Gieseke, Röhr, Siódmok, arXiv:1206.2205

Dijet Mass Distribution





CMS PAS EXO-12-059

ATLAS CONF-2012-148

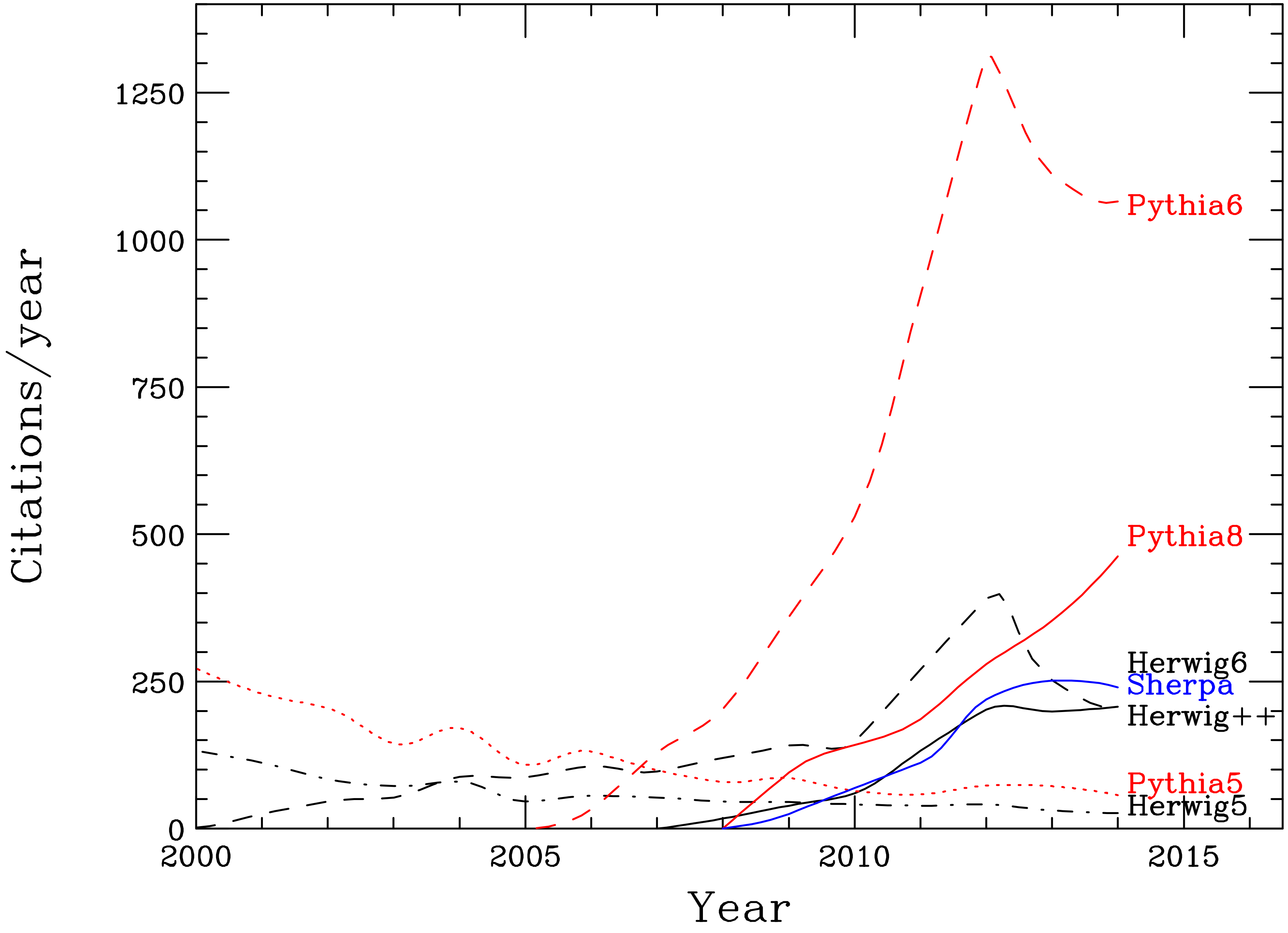
- No sign of deviation from Standard Model (yet)

Event Generators

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

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

Generator Citations



- Most-cited article only for each version
- 2014 is extrapolation (Jan to Aug x1.5)

Other relevant software

(with apologies for omissions)

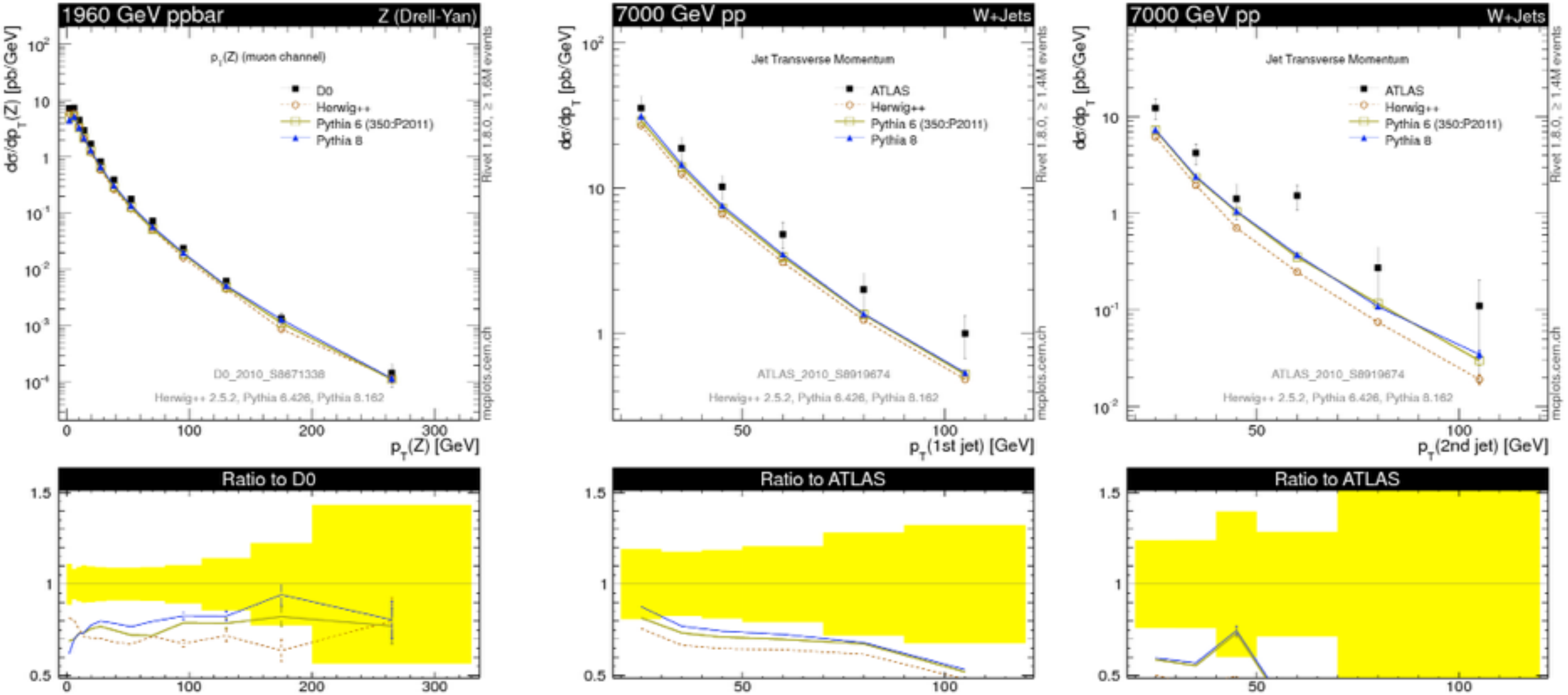
- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino, Charybdis, TrueNoir
- Mass spectra and decays: SOFTSUSY, SPHENO, HDecay, SDecay
- Feynman rule generators: FeynRules
- PDF libraries: LHAPDF
- Resummed ($p_\perp$) spectra: ResBos
- Approximate loops: LoopSim
- Jet finders: anti-$k_\perp$ and FastJet
- Analysis packages: Rivet, Professor, MCPLOTS
- Detector simulation: GEANT, Delphes
- Constraints (from cosmology etc): DarkSUSY, MicrOmegas
- Standards: PDF identity codes, LHA, LHEF, SLHA, Binoth LHA, HepMC

Sjöstrand, Nobel Symposium, May 2013

Parton Shower Monte Carlo

http://mcplots.cern.ch/

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



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

Summary on Event Generators

- Fairly good overall description of data, but…
- Hard subprocess: LO no longer adequate
- Parton showers: need matching to NLO
  - Also multijet merging
  - NLO showering?
- Hadronization: string and cluster models
  - Need new ideas/methods
- Underlying event due to multiple interactions
  - Colour reconnection necessary