SUSY QCD corrections to electroweak gauge boson production with an associated jet

Ryan Gavin
University of Wisconsin Madison

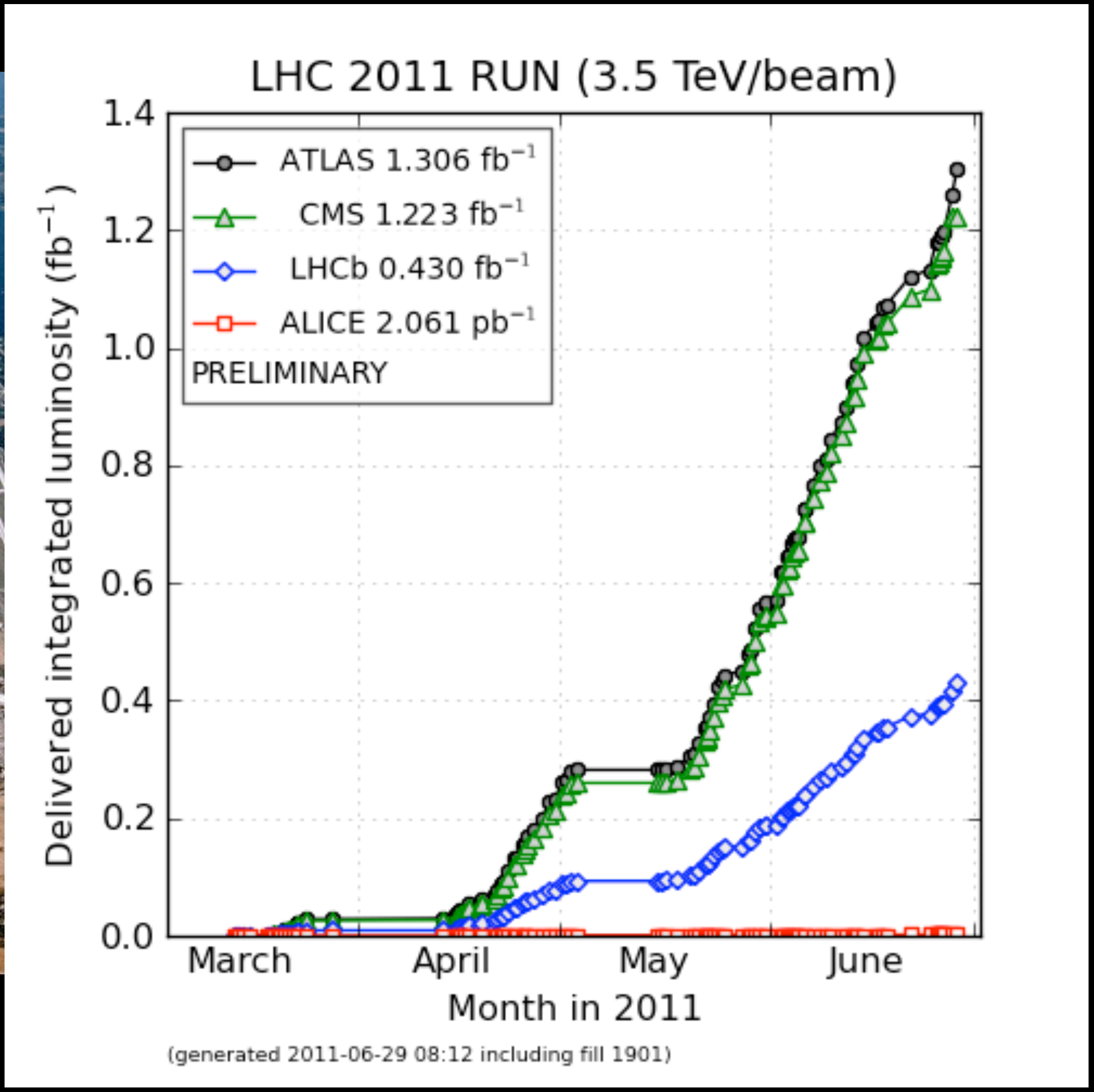
with F Petriello, M Trenkel
in progress

PSI Particle Theory Seminar
June 30, 2011

Outline

- EW Gauge Boson Production
- at Higher Orders
- sQCD Corrections to Z+Jet
- Numerical Results
- sQCD Corrections to W+Jet
- Concluding Remarks

The LHC



Running at 7 TeV since March 13, 2011

$$\mathcal{L}_{int} \sim 1.3\ \mathrm{fb}^{-1}$$

Z & W's at Hadron Colliders

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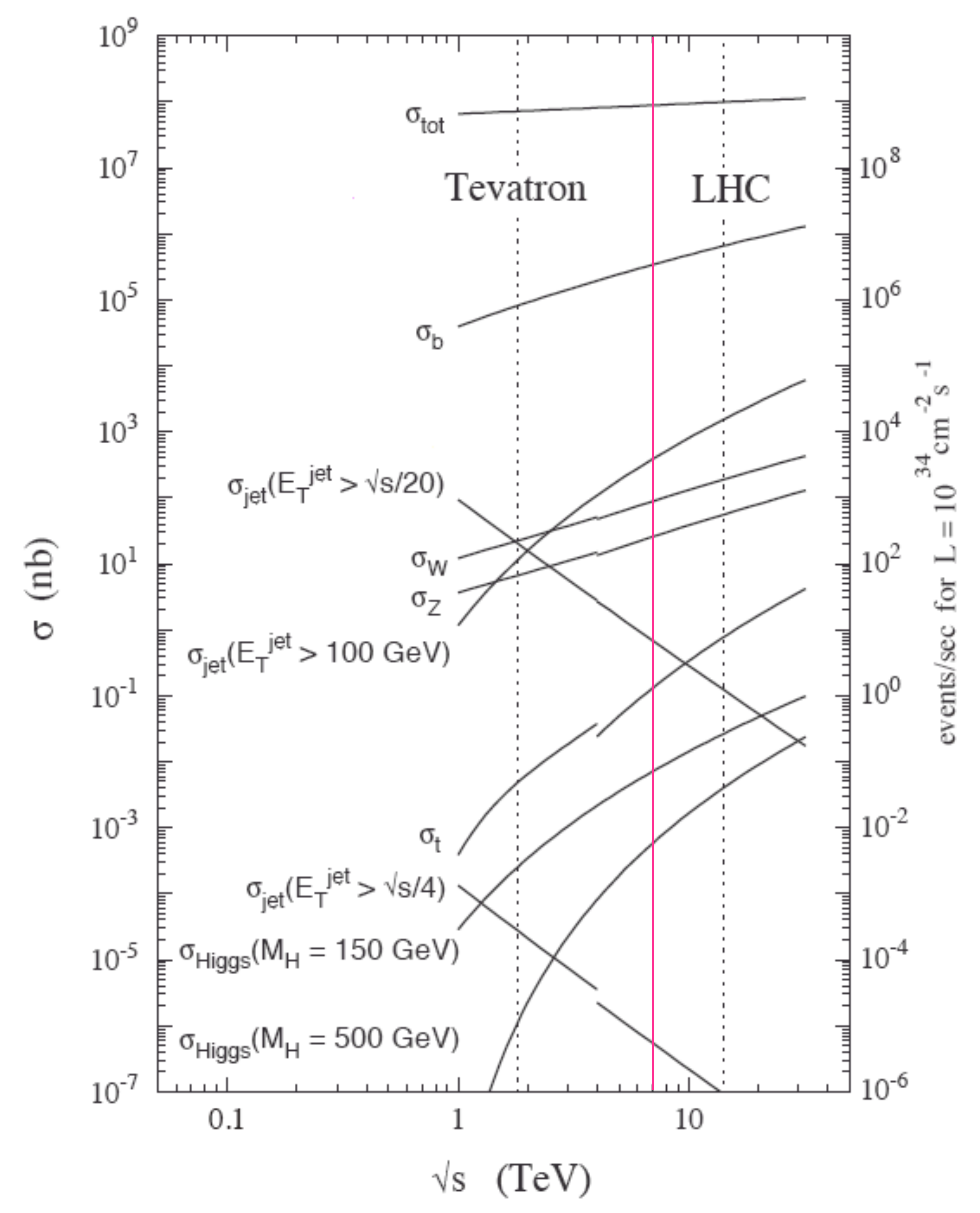
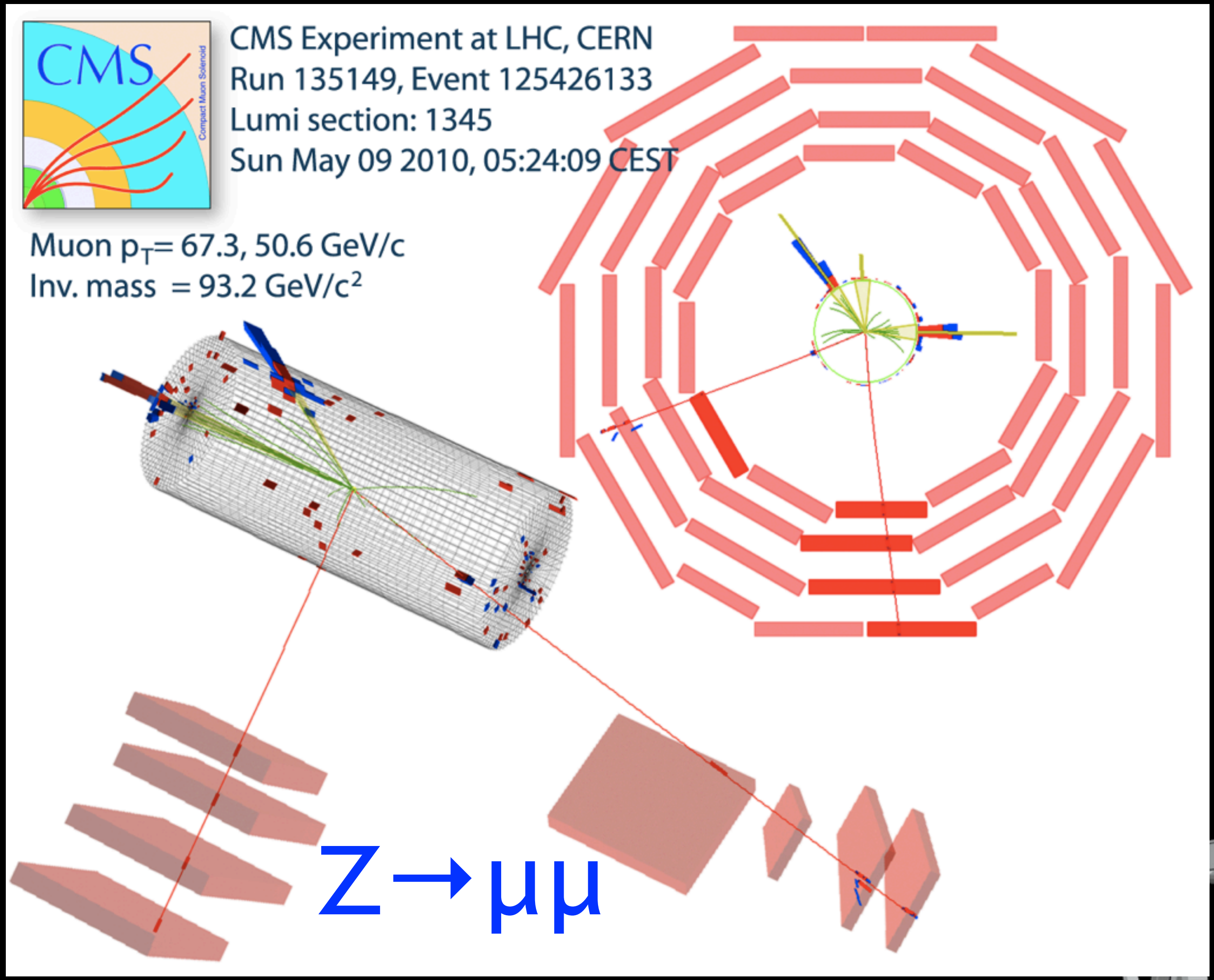
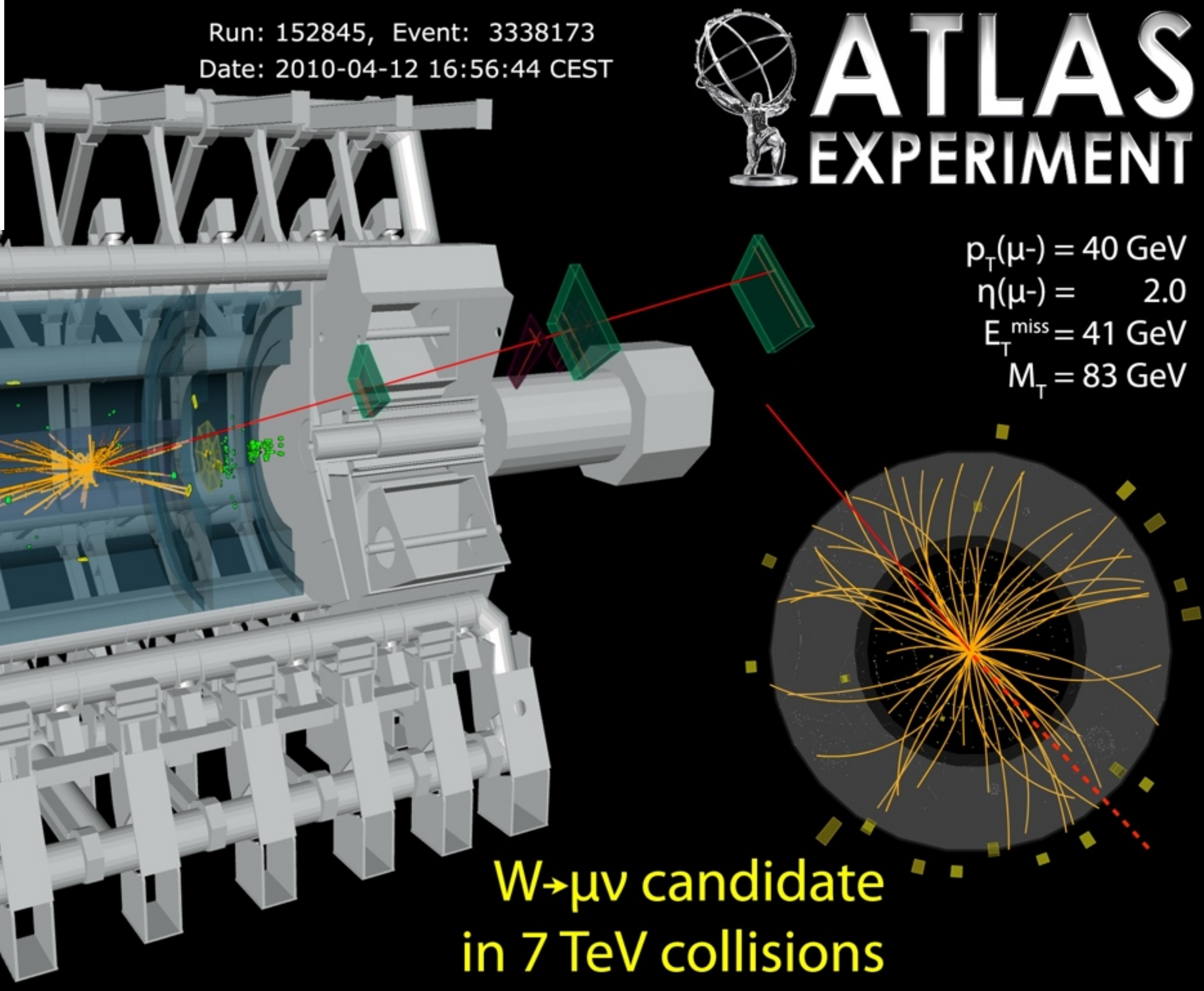
- σ_Z, σ_W
  - large production cross sections
  - 1 to 10's of nbs



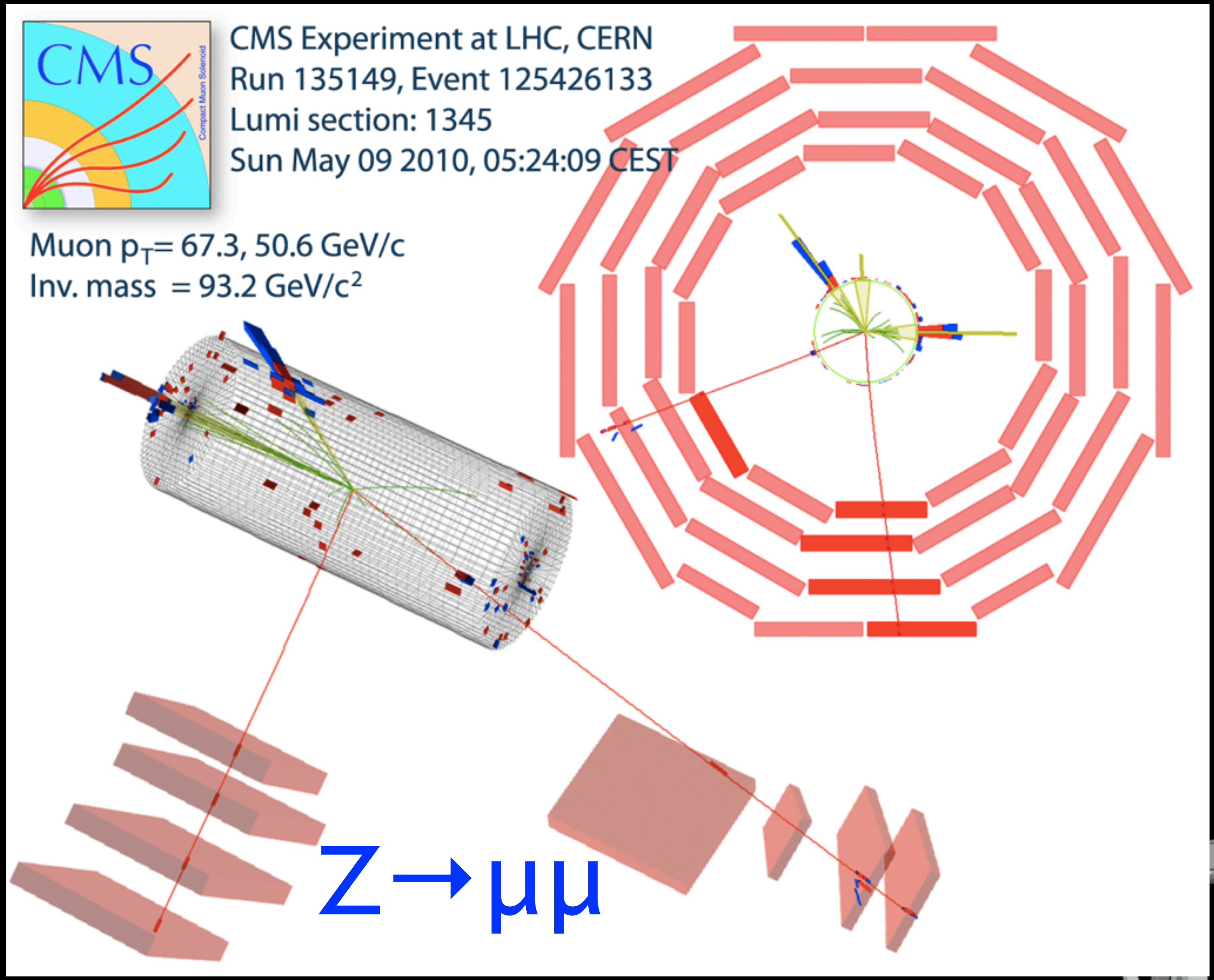


Z & W candidates



100k events/yr

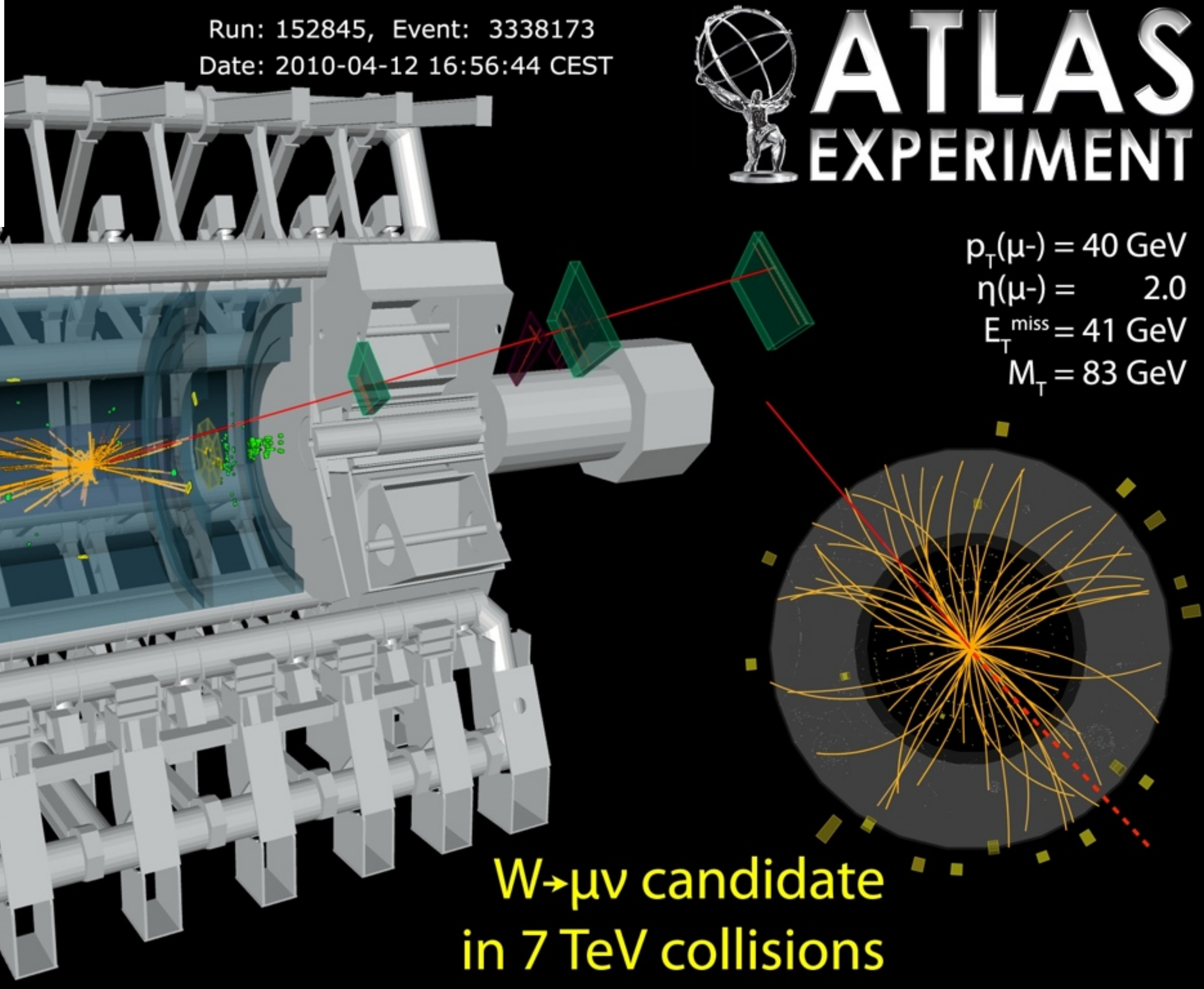
Z & W candidates



$Z \rightarrow \mu\mu$

Over
One Year Old!

100k events/yr

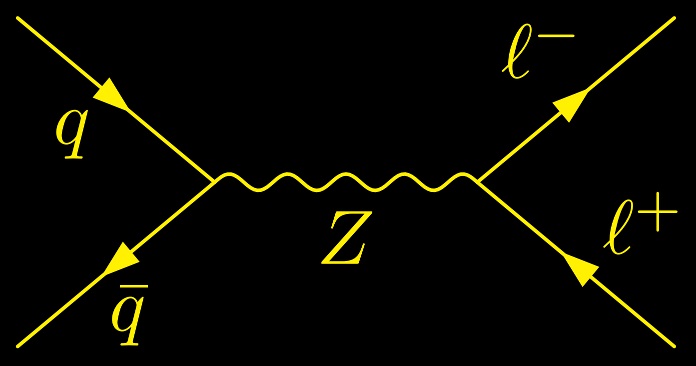


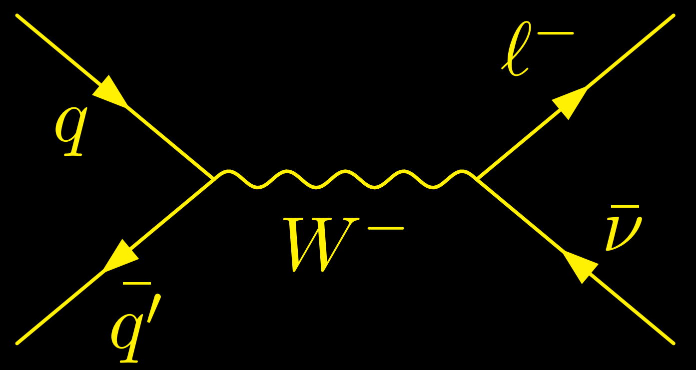
$W \rightarrow \mu\nu$ candidate
in 7 TeV collisions

Z & W's at Hadron Colliders

- Electroweak (EW) gauge boson production
  - decay to leptonic final state

leading order





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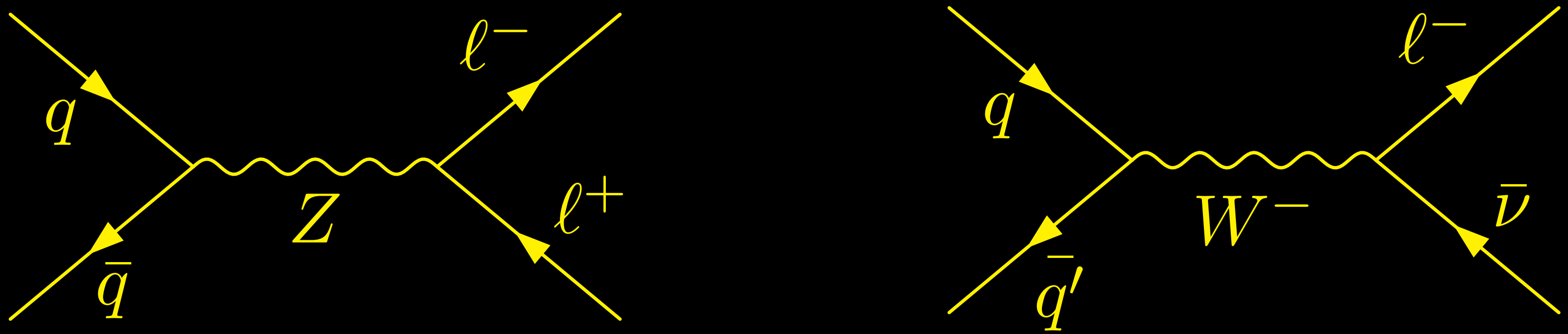

- Hadronic cross section

$$d\sigma_{AB} = \sum_{a,b} \int dx_a f_{a/A}(x_a, \mu_F) \int dx_b f_{b/B}(x_b, \mu_F)\; d\hat{\sigma}_{ab}$$

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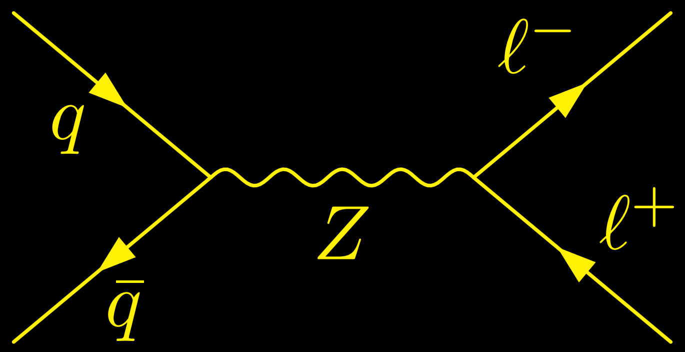

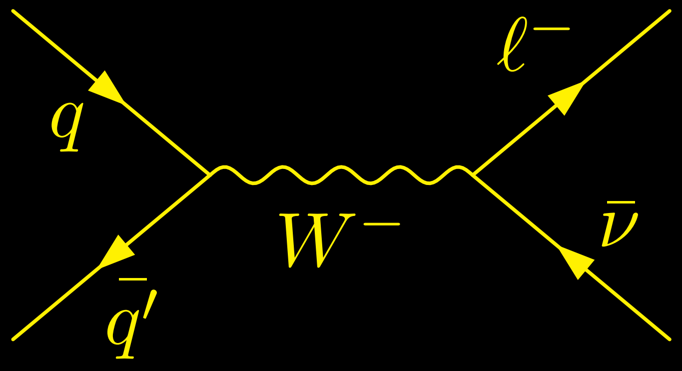

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parton distribution functions (PDF)

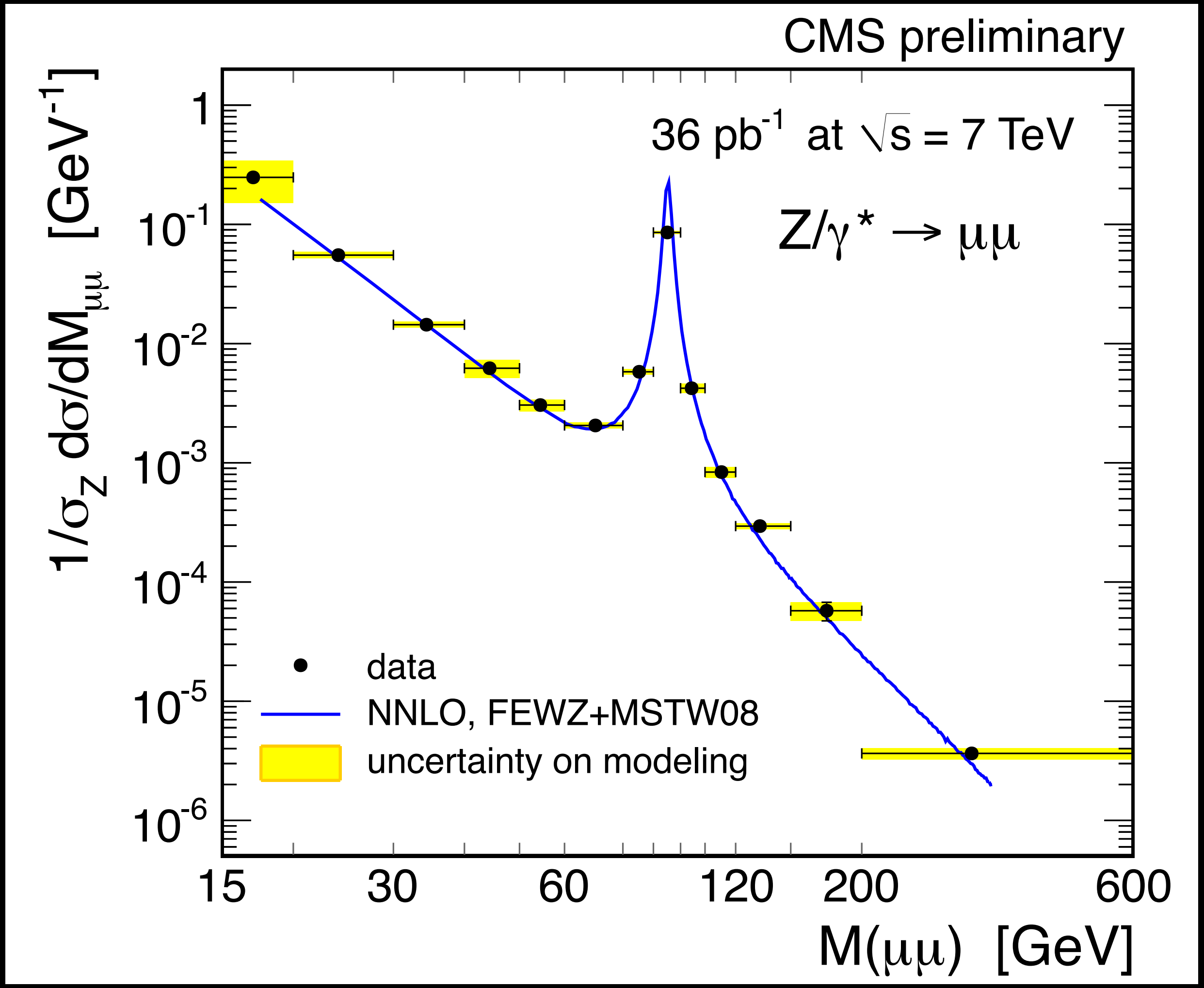
- probability to find a parton with momentum fraction x
- process independent
- μ_F factorization scale

Z & W's at Hadron Colliders

- Clear collider signature
  - leptonic final states

$$pp \rightarrow Z/\gamma^* \rightarrow l^- l^+$$

- two opposite sign candidates
- high p_T
- isolation & identification
- peak in $M_{l^+l^-}$



CMS PAS EWK-10-007

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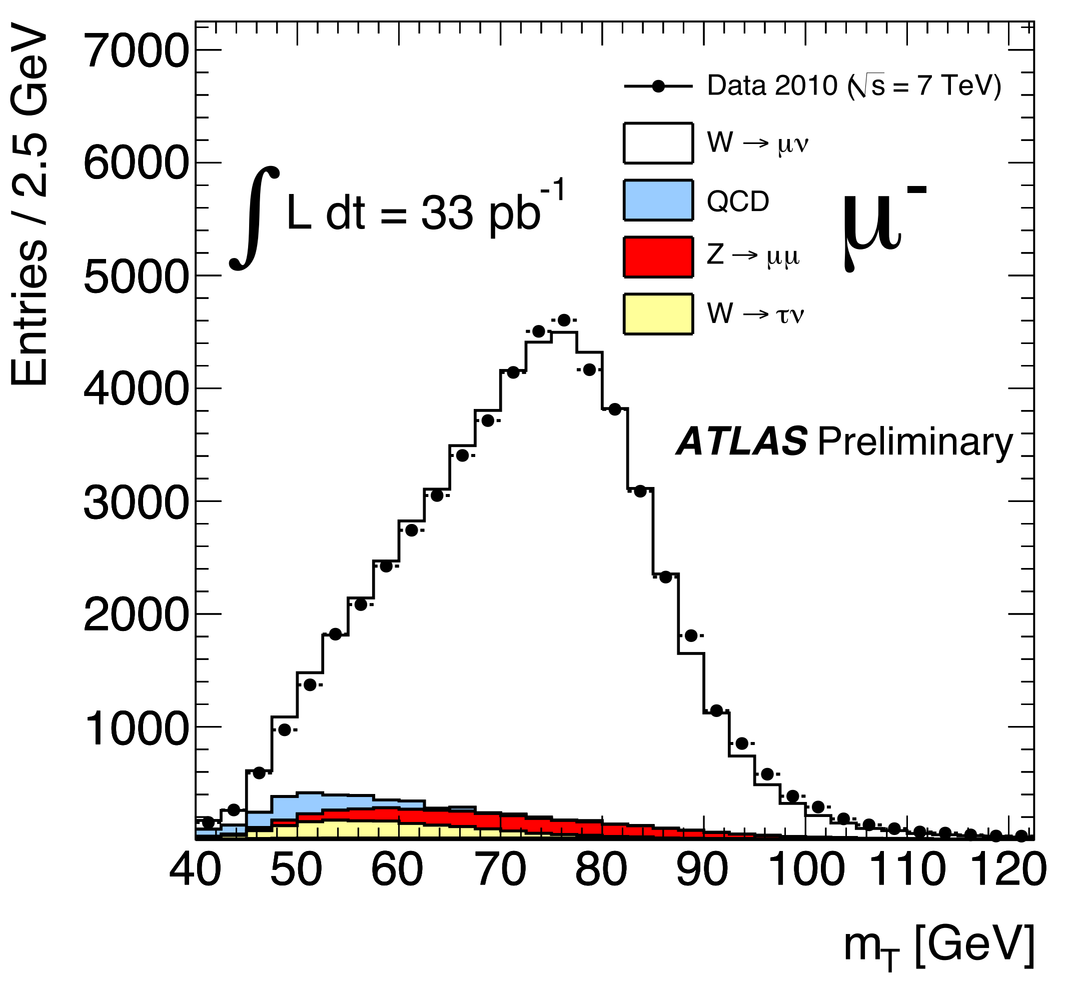

$$pp \rightarrow W^- \rightarrow l^- \bar{\nu}$$

- single charged candidate
- high lepton p_T
- lepton isolation & identification
- missing E_T
- peak in M_T

$$M_T = [2p^l_T p^\nu_T(1 - \cos\phi_{l\nu})]^{\frac{1}{2}}$$

ATLAS-CONF-2011-041

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- LHC 'Standard Candles'

Drell-Yan as Standard Candles

- Detector calibration & performance
  - M_Z, Γ_M from M_{ll} distributions at Z resonance
- Luminosity monitoring (Dittmar et. al.)
  - σ_W, σ_Z
- Important for measuring EW parameter
  - precise measurements of M_W, Γ_W, $\sin^2\theta_{eff}$
- Look at new analysis tools
  - a_T, $\phi_\eta^* \rightarrow$ low Z p_T study
  - reduce uncertainty due to energy resolution

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  - p_T distributions
  - Z pT > 0 starting at NLO

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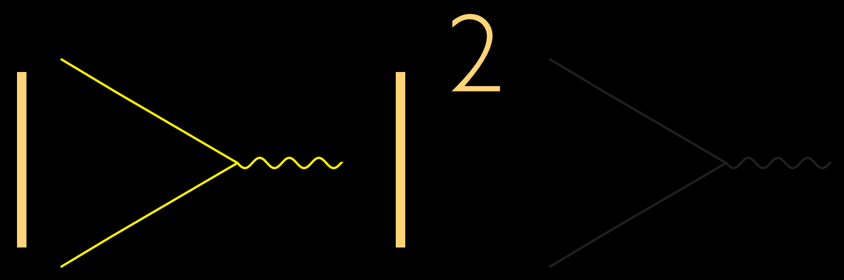

LO piece

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NLO contributions

Drell-Yan as Standard Candles

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$$\searrow$$

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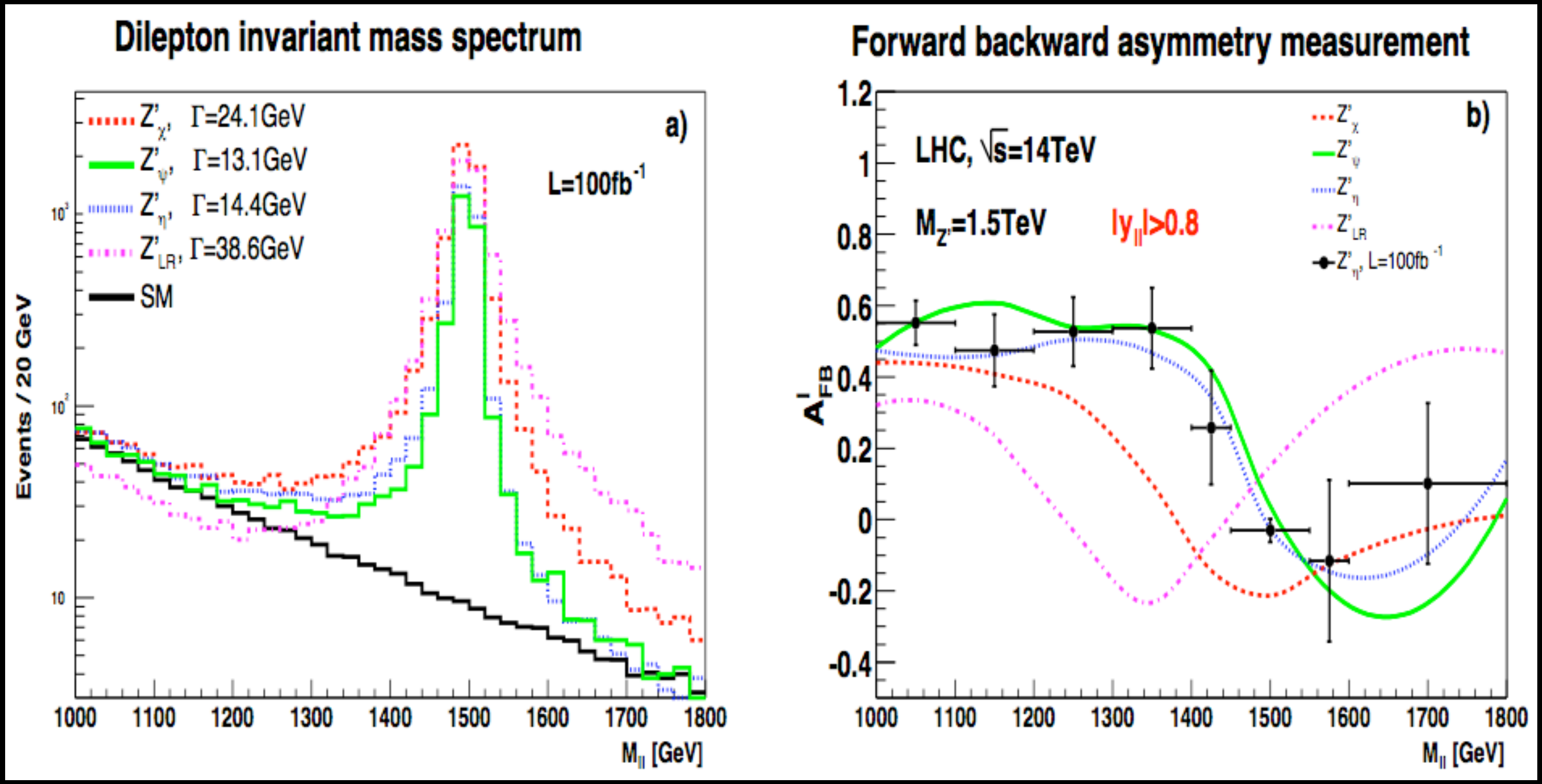
- Distributions in rapidity
  - measure/constrain PDFs

Drell-Yan as Standard Candles

- Constraint on some BSM physics
  - deviations in M_{ll} distributions (e.g. Z′)
  - deviations in forward/backward asymmetry, A_{FB}



Dittmar, Nicollerat, Djouadi
arXiv:hep-ph/0307020

Need for Higher Order?

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- Can expect percent level physics
  - need to reduce theoretical uncertainties

Need for Higher Order?

- Measurements require theory input

- Acceptances derived from calculation and simulation

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$$\sigma = \frac{N_{sig}}{\epsilon \cdot A \cdot \mathcal{L}_{int}}$$

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- Quantitative predictive power begins at NLO
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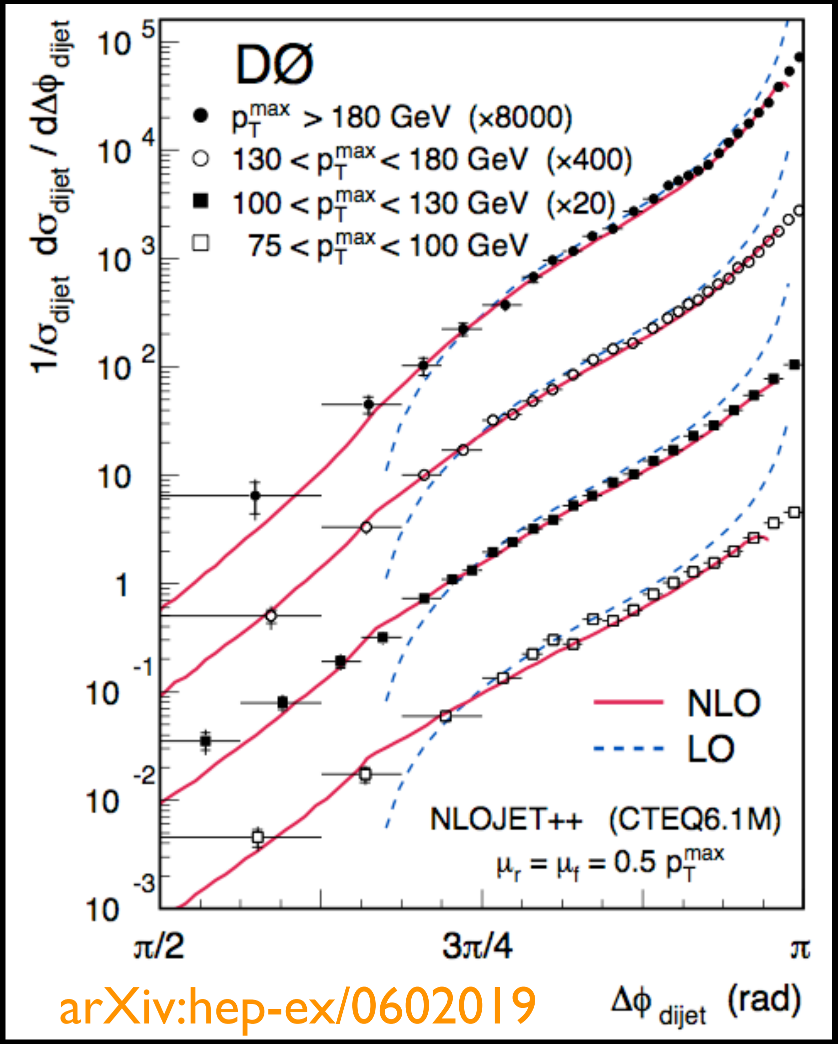

arXiv:hep-ex/0602019

dijet production

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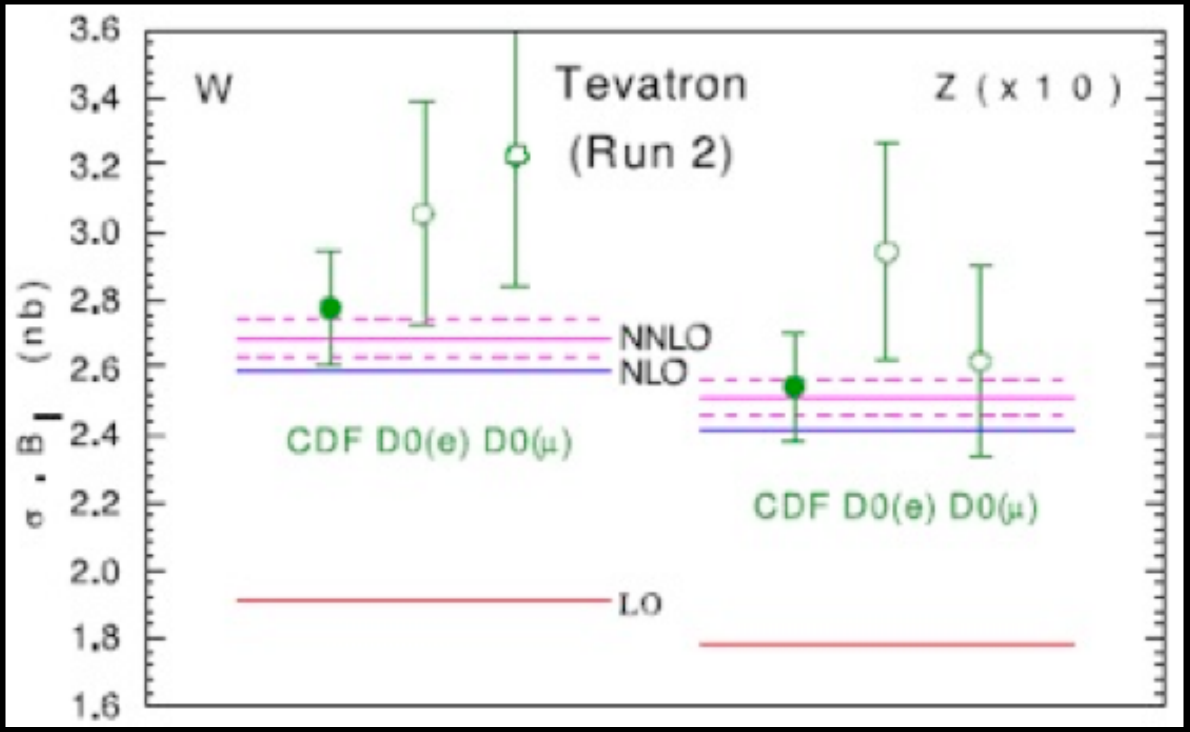

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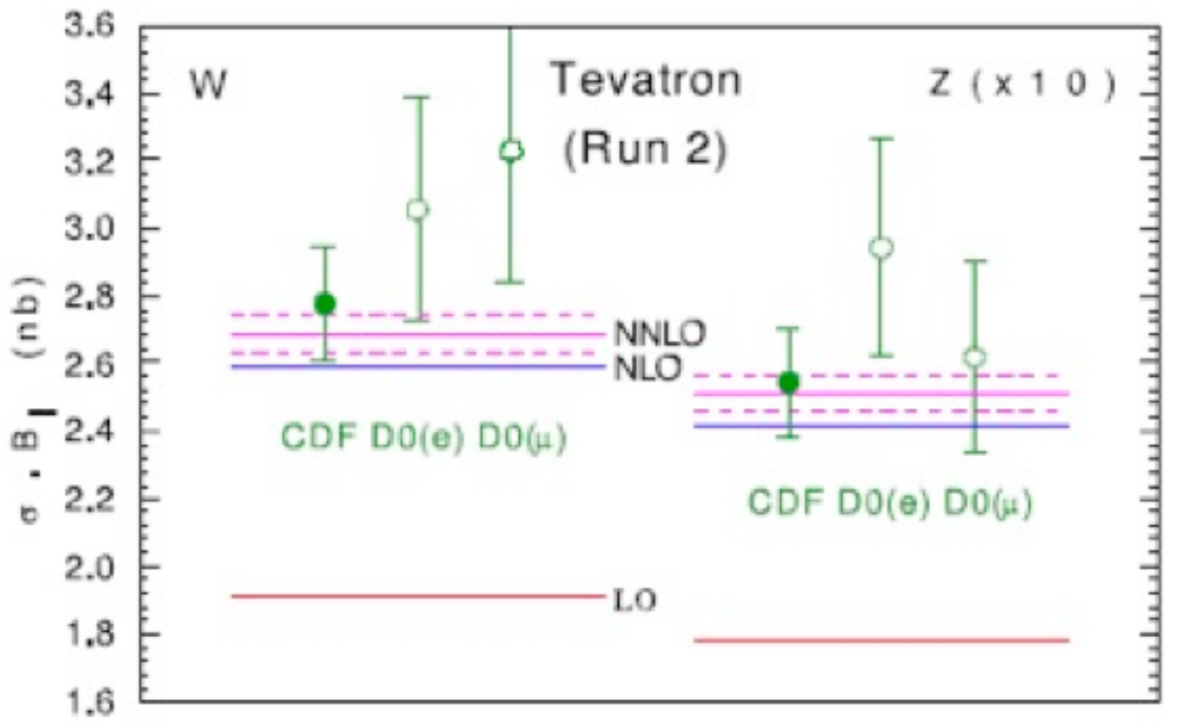

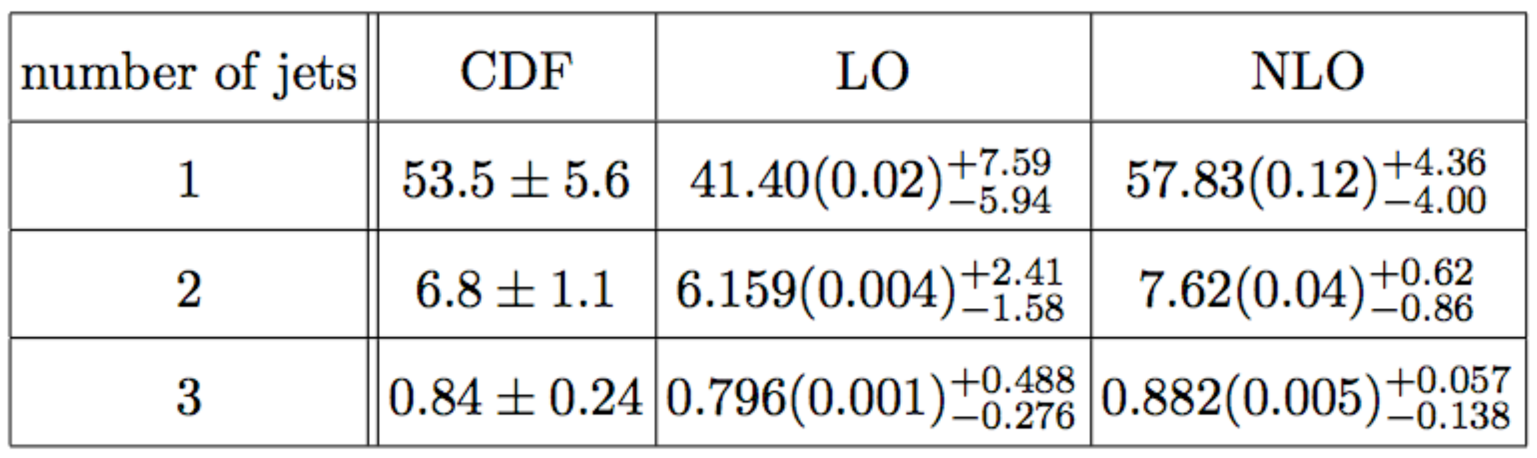

number of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

← inclusive cross section for W + n jets (pb)

Berger, et al.
arXiv:0907.1984

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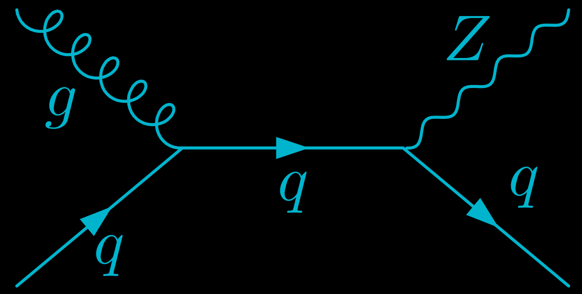

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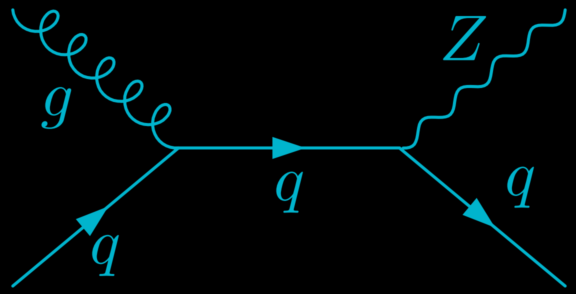
- Background to new physics searches



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3 partonic processes

$$q\,\bar{q} \to Z/\gamma^*\,g \to \ell^-\ell^+\,g$$
$$g\,q \to Z/\gamma^*\,q \to \ell^-\ell^+\,q$$
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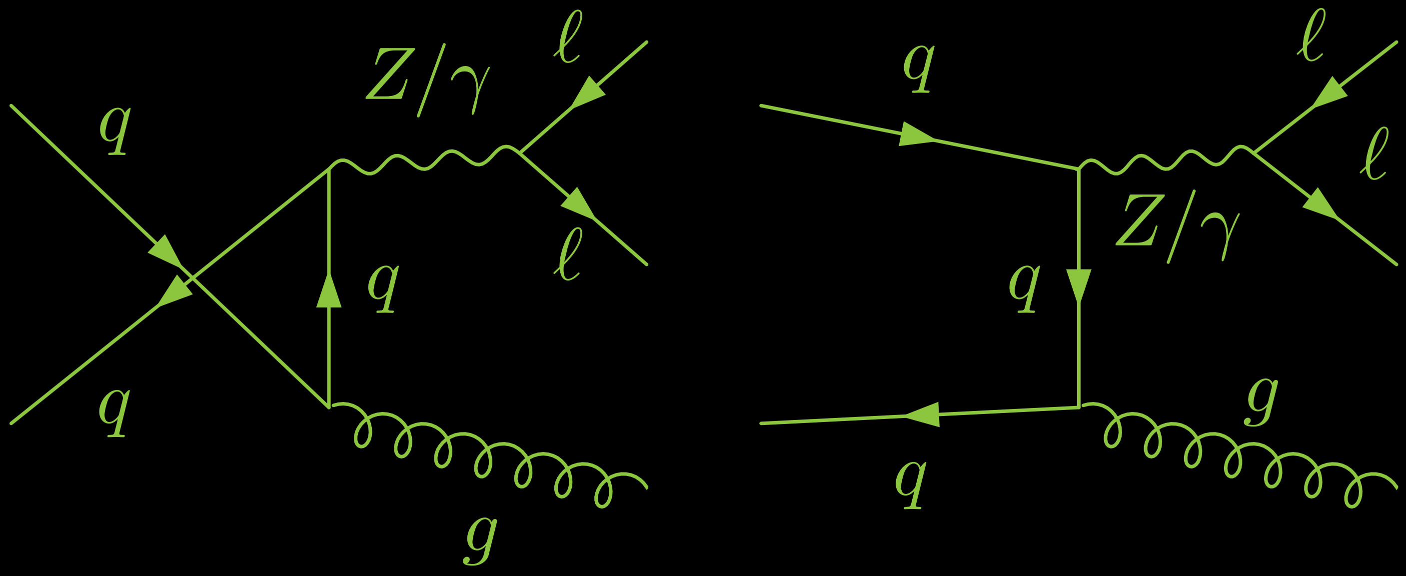
$\underline{q\bar{q}}$:



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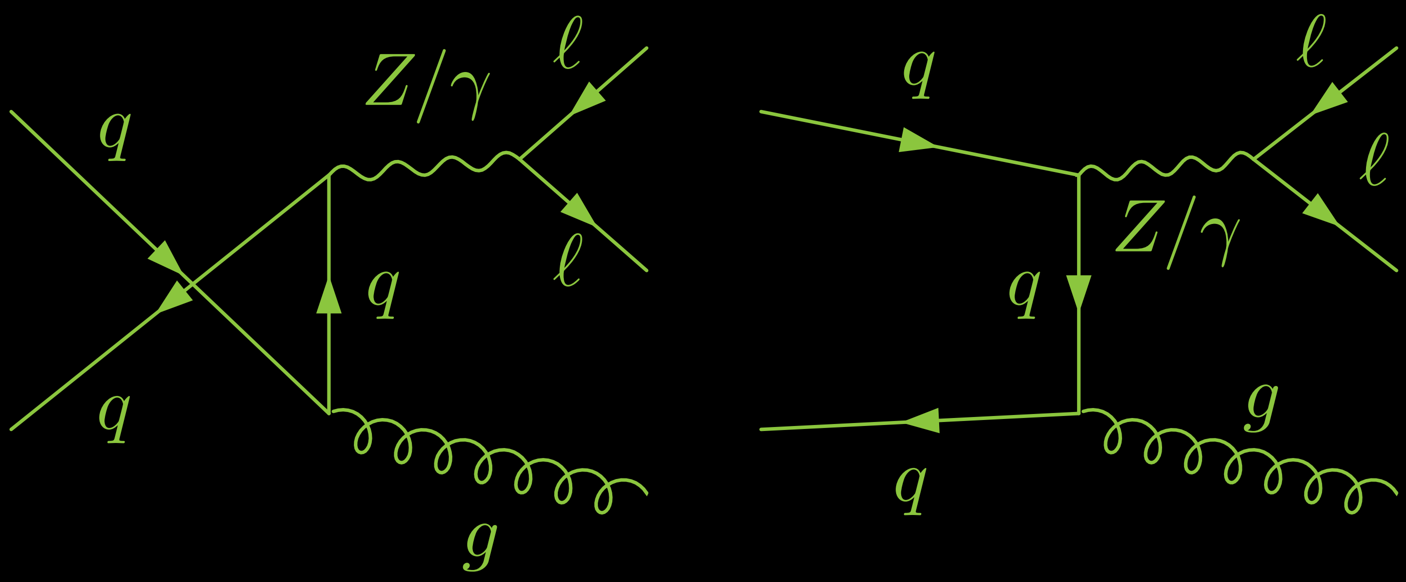
diagrams obtained by quark and antiquark crossing with gluon

$\underline{q\bar{q}}$:



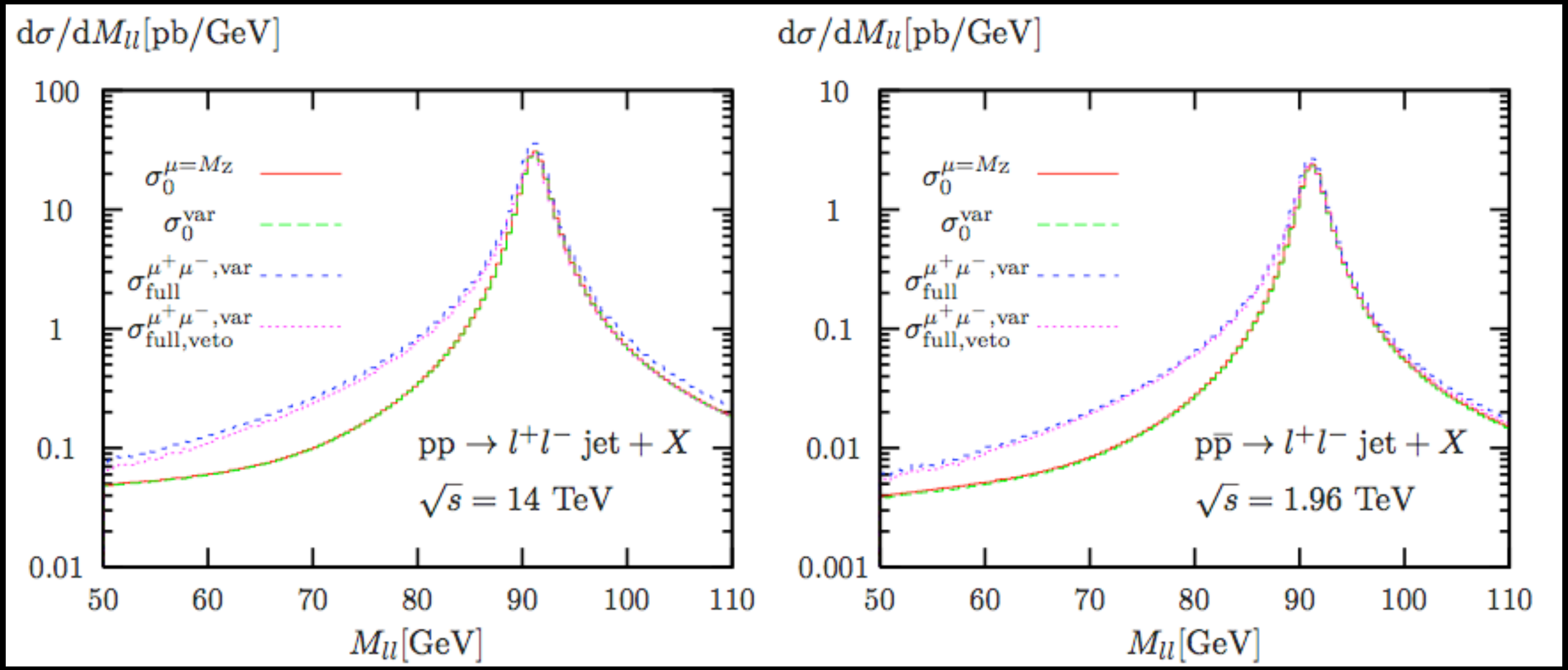
Z+Jet at NLO

- Quantitative predictive power begins at NLO
- Studies in EW & QCD NLO corrections

Denner, Dittmaier, Kasprzik, Muck - arXiv:1103.0914

  - QCD: σ_{int} ~ 35%
  - EW: σ_{int} ~ -3 to -5%

} variation in differential distributions



New Physics Contributions

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  - calculate supersymmetric QCD corrections to Z+jet

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- Consider Z+jet in the supersymmetric framework
  - calculate supersymmetric QCD corrections to Z+jet
- Goal: Investigate stability of Z+jet as a standard candle under sQCD corrections

Supersymmetry

- Symmetry relating fermions and bosons
- Solution to hierarchy problem
  - SM quadratic corrections to Higgs mass cancel against corrections from supersymmetric partners
- Gauge coupling unification (weak scale soft SUSY breaking)
- Dark matter candidate with *R*-parity conservation

$$P_R = (-1)^{3(B-L)+2s}$$

B - baryon #
L - lepton #
s - spin

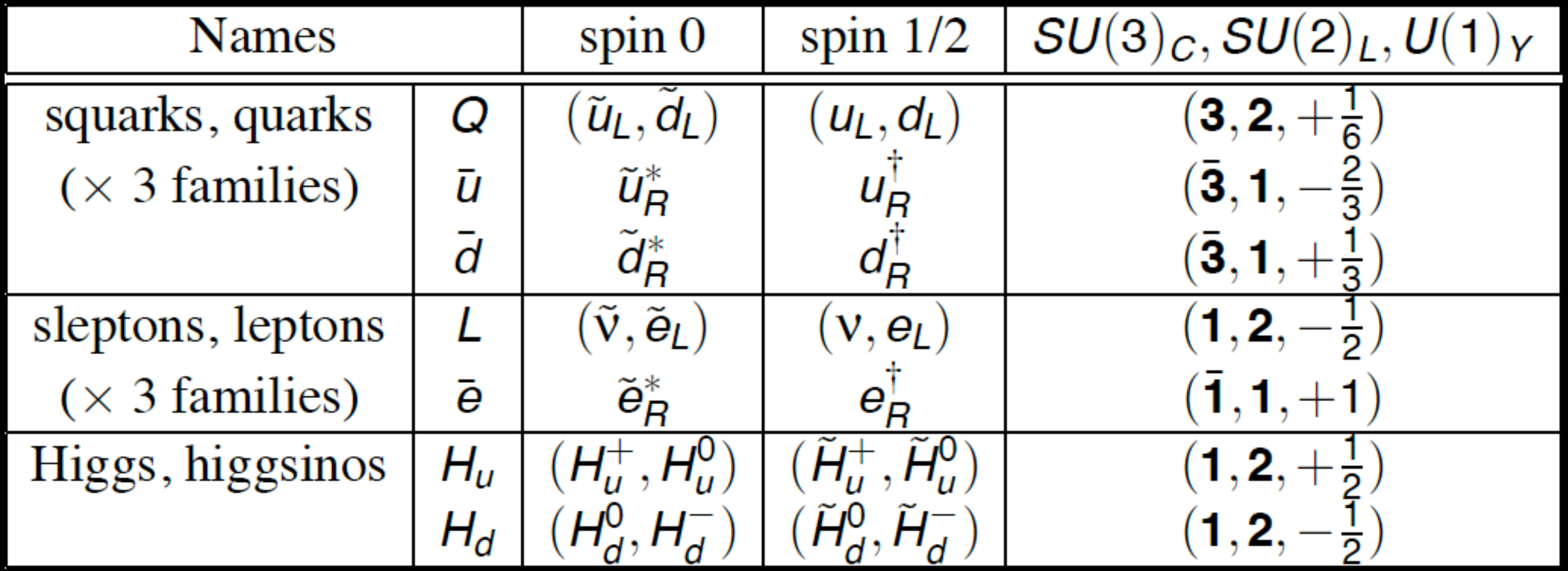
$\text{SM particle: } P_R = 1$ $\qquad$ $\text{SUSY particle: } P_R = -1$

The MSSM

- Minimal Supersymmetric extension of the Standard Model
  - only 1 superpartner for each SM particle
  - anomaly free
  - supersymmetry is softly broken
  - *R*-parity conserved

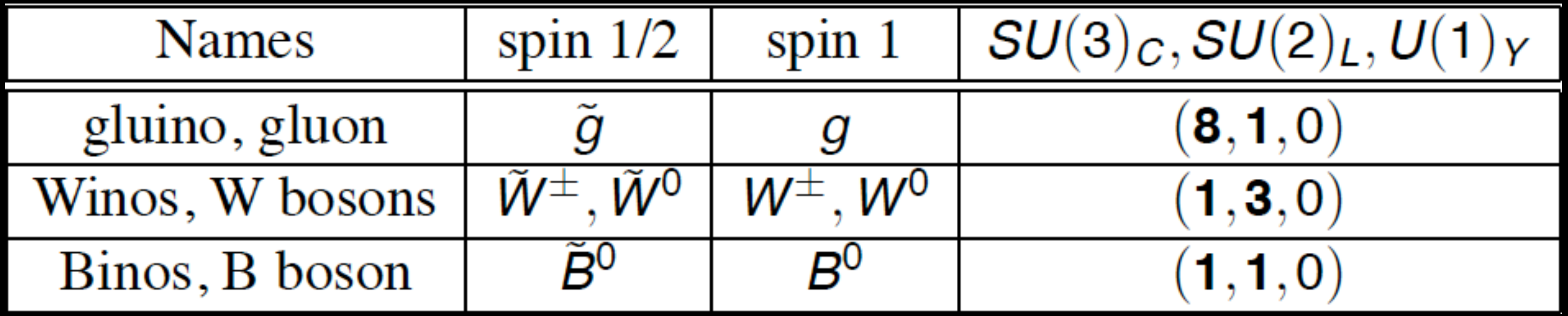
MSSM Particle Content

chiral superfields



Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(\mathbf{3}, \mathbf{2}, +\frac{1}{6})$
($\times$ 3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, +\frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times$ 3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\bar{\mathbf{1}}, \mathbf{1}, +1)$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

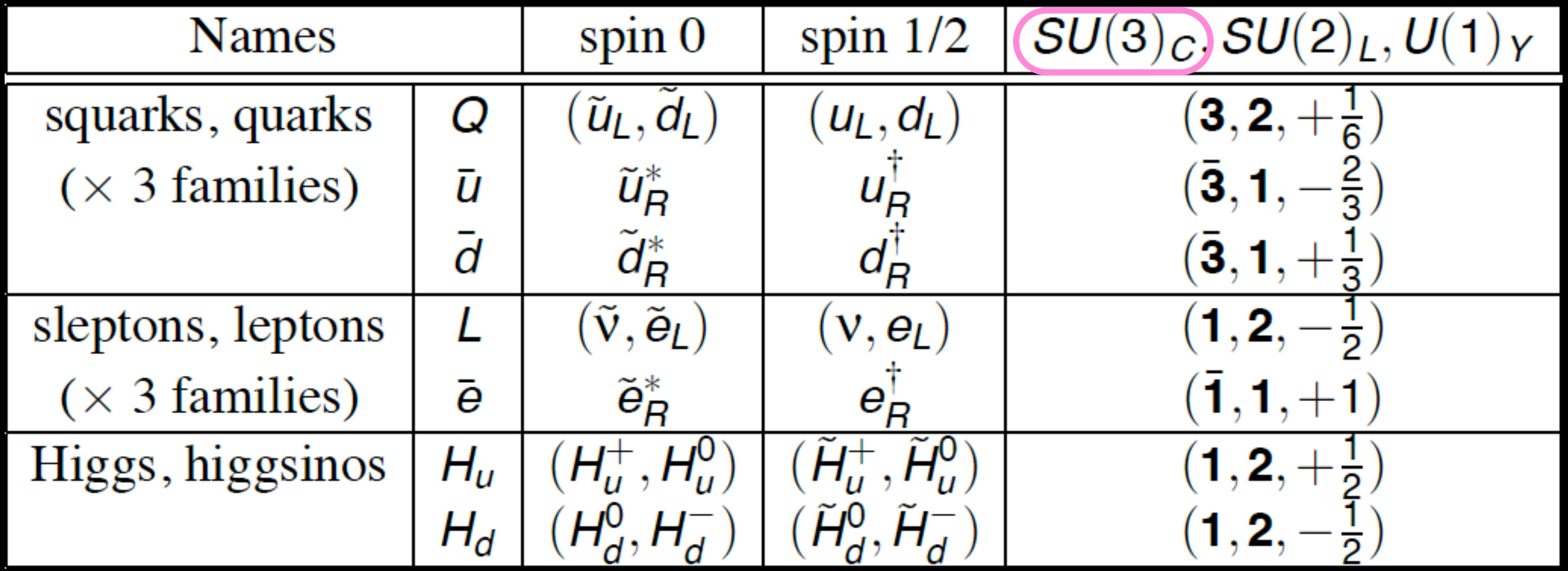
vector superfields



Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
Winos, W bosons	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
Binos, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

MSSM Particle Content

chiral superfields



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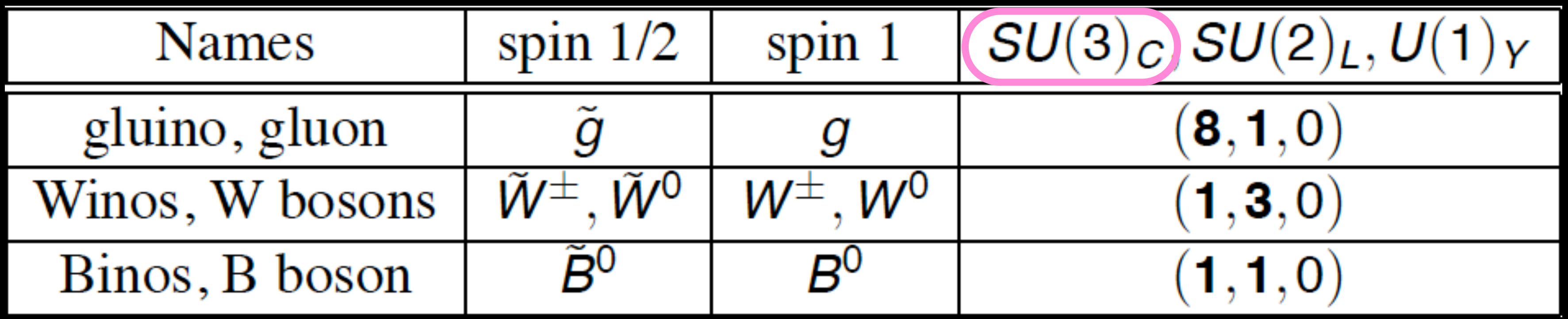
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

interested in QCD-like corrections to Z+1 jet

what's charged under $SU(3)_C$?

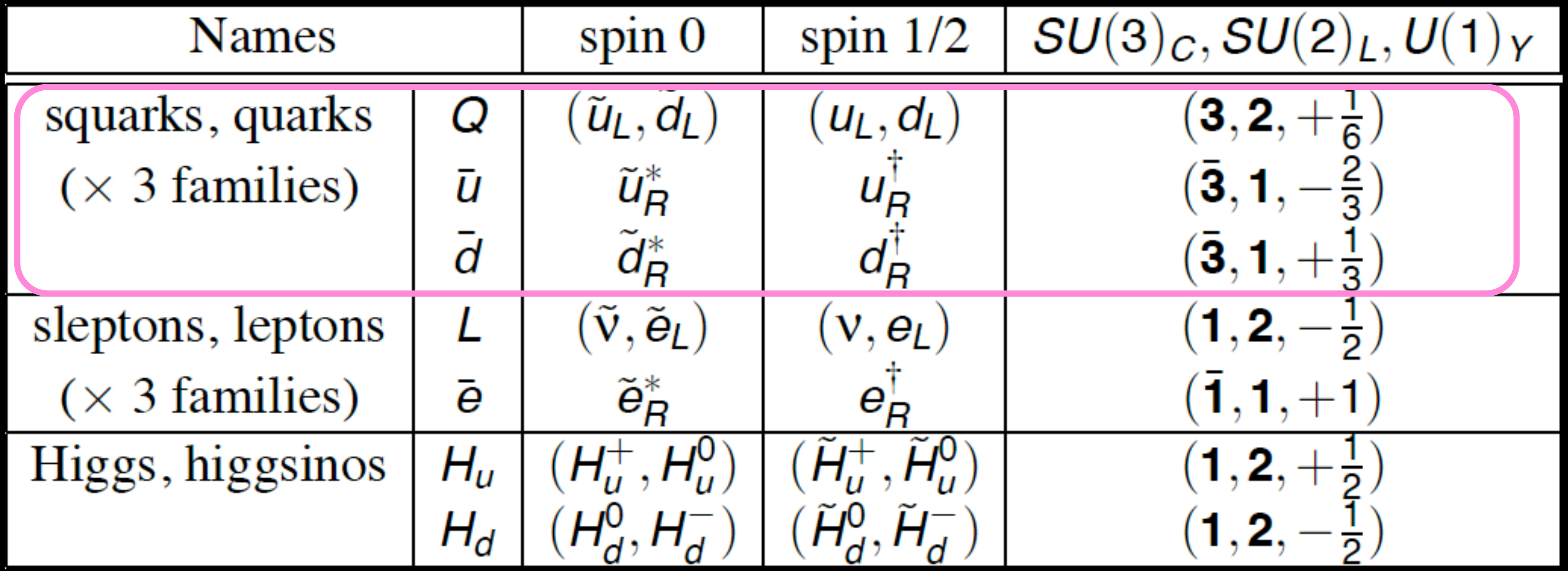
vector superfields



Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
Winos, W bosons	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
Binos, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

MSSM Particle Content

chiral superfields

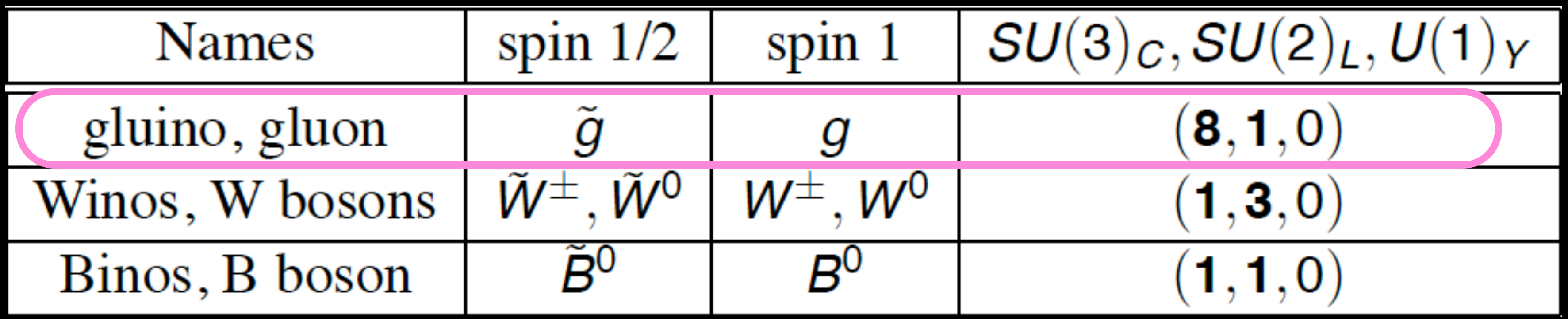


Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(\mathbf{3}, \mathbf{2}, +\frac{1}{6})$
(× 3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, +\frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(× 3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\bar{\mathbf{1}}, \mathbf{1}, +1)$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

interested in QCD-like corrections to Z+1 jet

what's charged under $SU(3)_C$?

vector superfields



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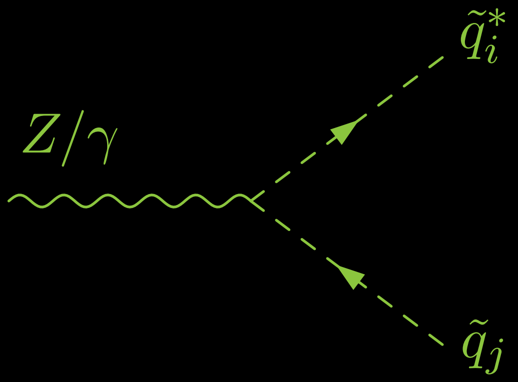
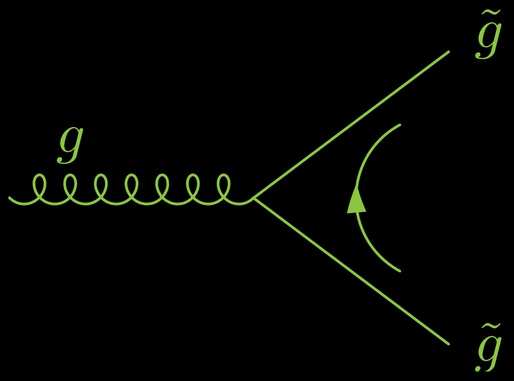
sQCD NLO Calculation

- supersymmetric QCD corrections
  - squarks, $\tilde{q}_i$ & gluinos, $\tilde{g}$
- SM / SUSY interactions

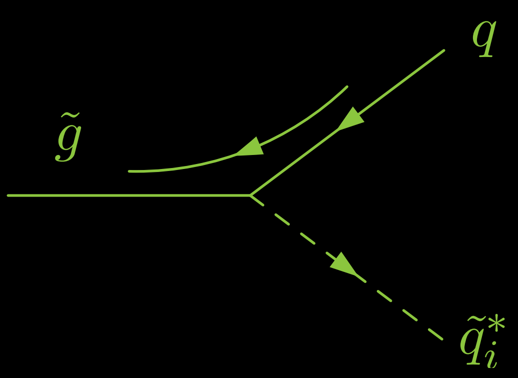
$\underline{Z\ \tilde{q}\ \tilde{q}}$



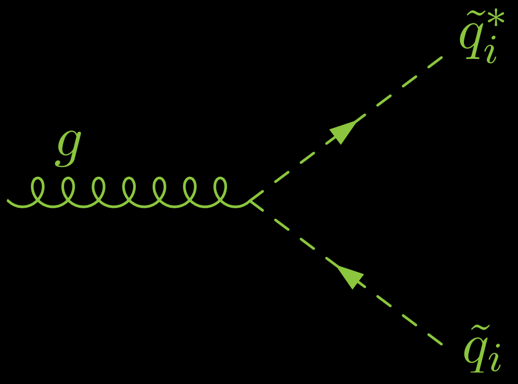
$\underline{g\ \tilde{g}\ \tilde{g}}$



$\underline{q\ \tilde{q}\ \tilde{g}}$



$\underline{g\ \tilde{q}\ \tilde{q}}$



sQCD NLO Calculation

- Conventional diagrammatic approach used
- Two independent calculations performed

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  - FeynArts, FeynCalc, LoopTools

hep-ph/0012260, hep-ph/0105349,
hep-ph/9807565

sQCD NLO Calculation

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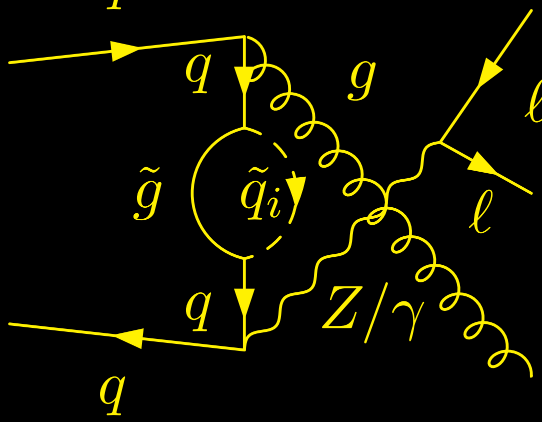
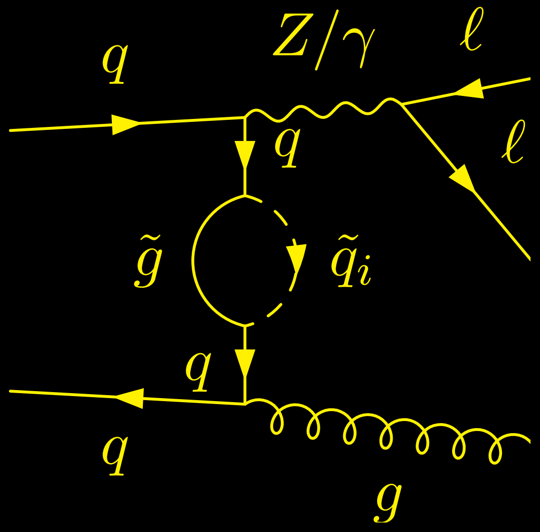
- Two independent calculations performed
  - FeynArts, FeynCalc, LoopTools hep-ph/0012260, hep-ph/0105349, hep-ph/9807565
  - QGRAF P. Nogueira
  - in-house software using Form & Maple
  - loops dealt with using AIR & QCDLoop library

hep-ph/0404258, arXiv:0712.1851

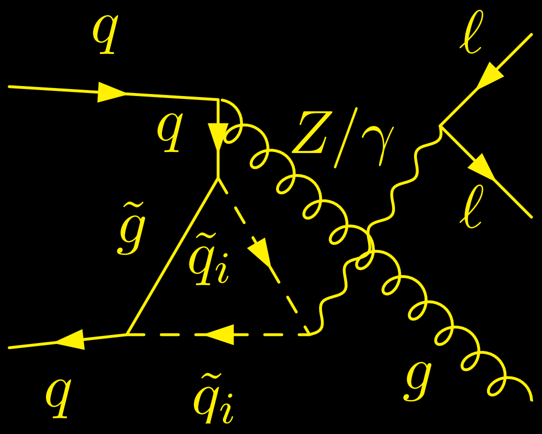
Loop Diagrams

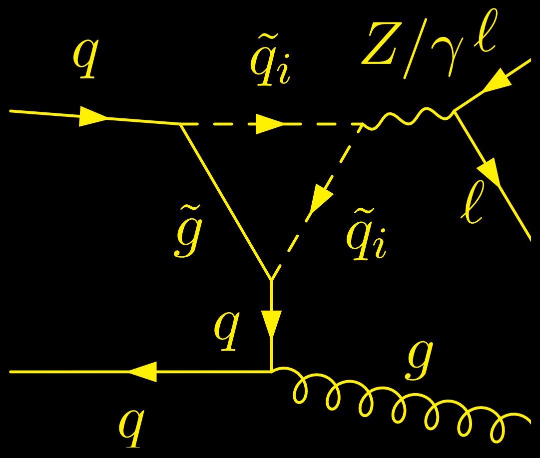
Self-energy Insertions





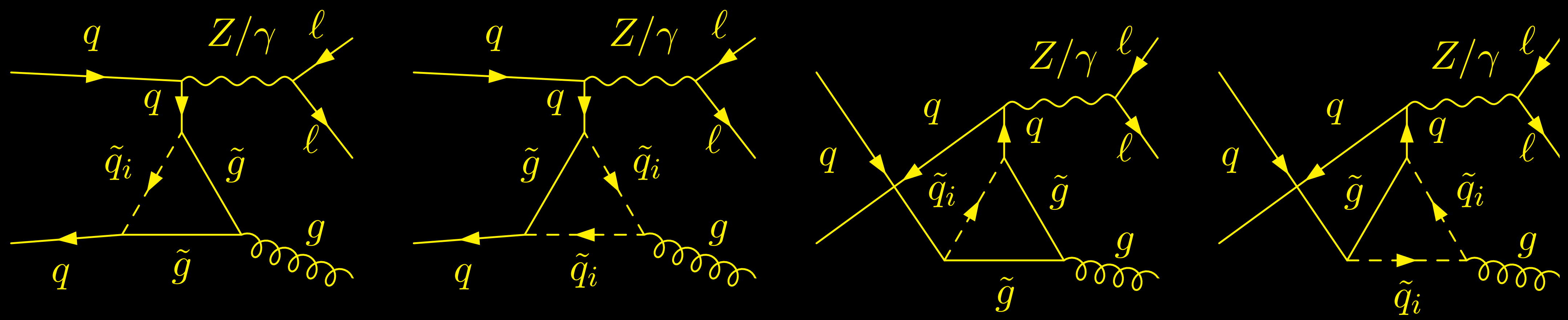
Z-Vertex Corrections



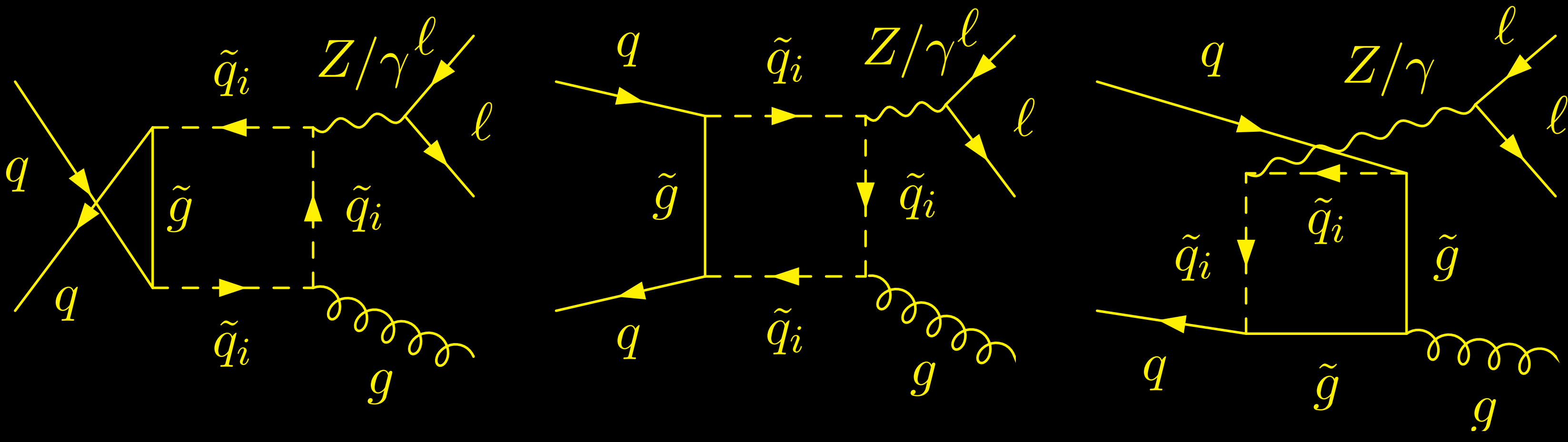


Loop Diagrams

Gluon-Vertex Corrections



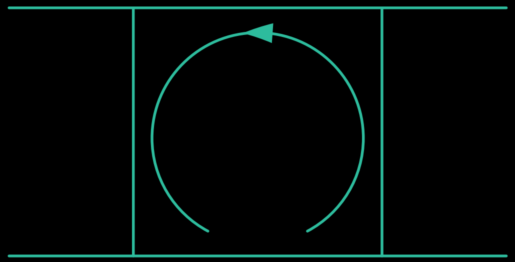
Box Corrections



Loop Integrals

- Tensor and scalar integrals present in calculation
  - reduce tensor integrals into scalar integrals
    - Automated Integral Reduction (AIR) hep-ph/0404258
- All loop integrals are reduced to a set of master scalar integrals
- QCDloop used in numerical evaluation of scalar loop integrals arXiv:0712.1851

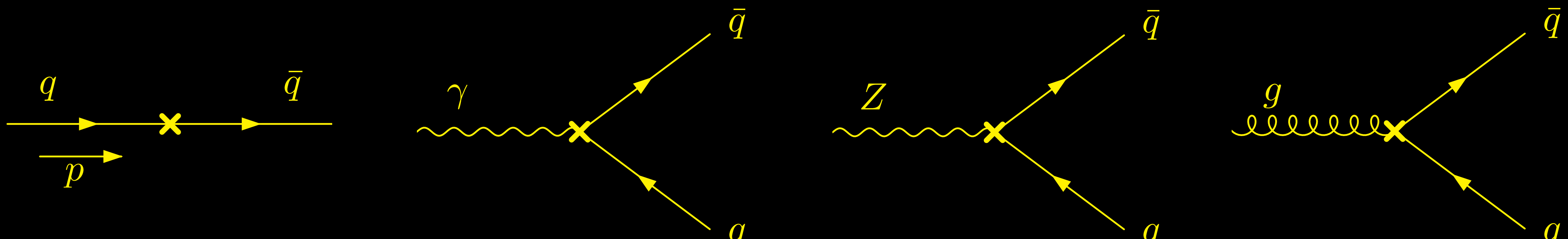
Singularities



- Massive particles propagating in the loop
  - no soft or collinear (IR) singularities
  - no real emission contribution
- Ultraviolet (UV) divergences do emerge from loop integrals
  - isolate UV singular structure using dimensional regularization
    - work in $d = 4 - 2\varepsilon$ dimensions

Renormalization

- Self-energy insertions and vertex corrections divergent
  - boxes are finite
- redefine quark and gluon fields, and strong coupling to absorb UV divergences
  - add counterterm diagrams to cancel singularities



γ^5 in d-Dimensions

- γ^5 not well defined for $d \neq 4$
- Used non-anticommuting γ^5 scheme Larin: hep-ph/9302240

$$\gamma^5 = \frac{i}{4!}\epsilon_{\mu\nu\rho\sigma}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma$$

- Need to symmetrize axial current

$$\gamma^\mu\gamma^5 \to \frac{1}{2}(\gamma^\mu\gamma^5 - \gamma^5\gamma^\mu)$$

  - using identity above

$$\gamma^\mu\gamma^5 \to \frac{i}{3!}\epsilon_{\mu\nu\rho\sigma}\gamma^\nu\gamma^\rho\gamma^\sigma$$

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$$\gamma^\mu\gamma^5 \to \frac{i}{3!}\epsilon_{\mu\nu\rho\sigma}\gamma^\nu\gamma^\rho\gamma^\sigma$$

Note: Other calculation approach used naive anticommuting scheme

$$\{\gamma^\mu, \gamma^5\} = 0$$

where 4-dimensional

$$\mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5] = -4i\epsilon^{\mu\nu\rho\sigma}$$

remains

Numerical results in agreement

Numerical Results

Preliminary

- $p_{T,jet} > 20$ GeV, $|\eta_{jet}| < 2.5$
- $M_{l^+l^-} > 50$ GeV
- CTEQ6M PDF set
- $\mu_R = \mu_F = M_Z$
- $\alpha_s(M_Z) = 0.118$
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$\sigma_{int} = 124.1$ pb

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msg = 600 GeV
msq = 500 GeV

sQCD corr = 8.784 fb

$\delta_{\mathrm{rel}} = 0.007\%$

$$\delta_{rel} = \frac{\mathcal{O}_{LO+sQCD} - \mathcal{O}_{LO}}{\mathcal{O}_{LO}}$$

all squark masses equal
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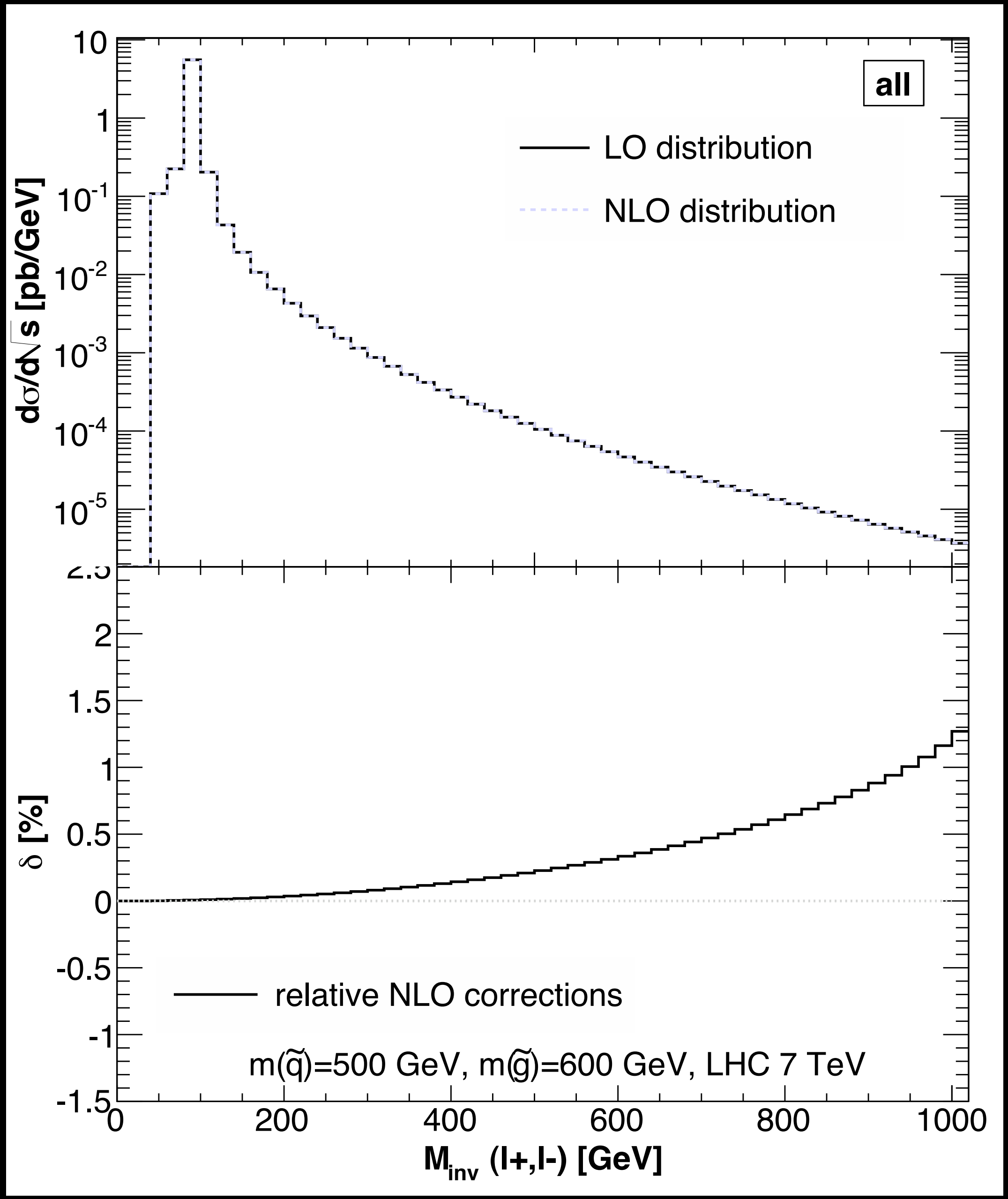
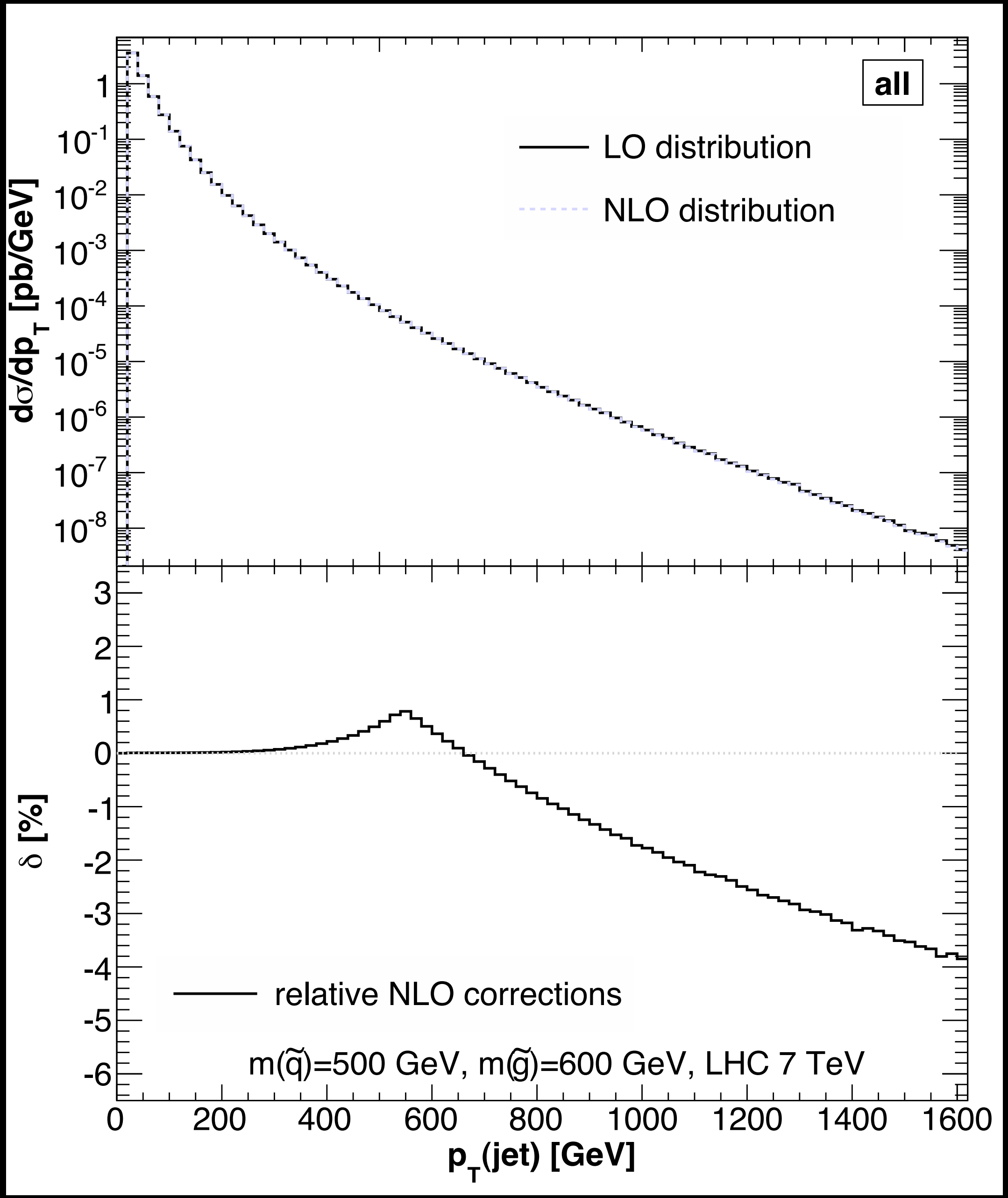
Kinematic Distributions

Preliminary

M_{ll}

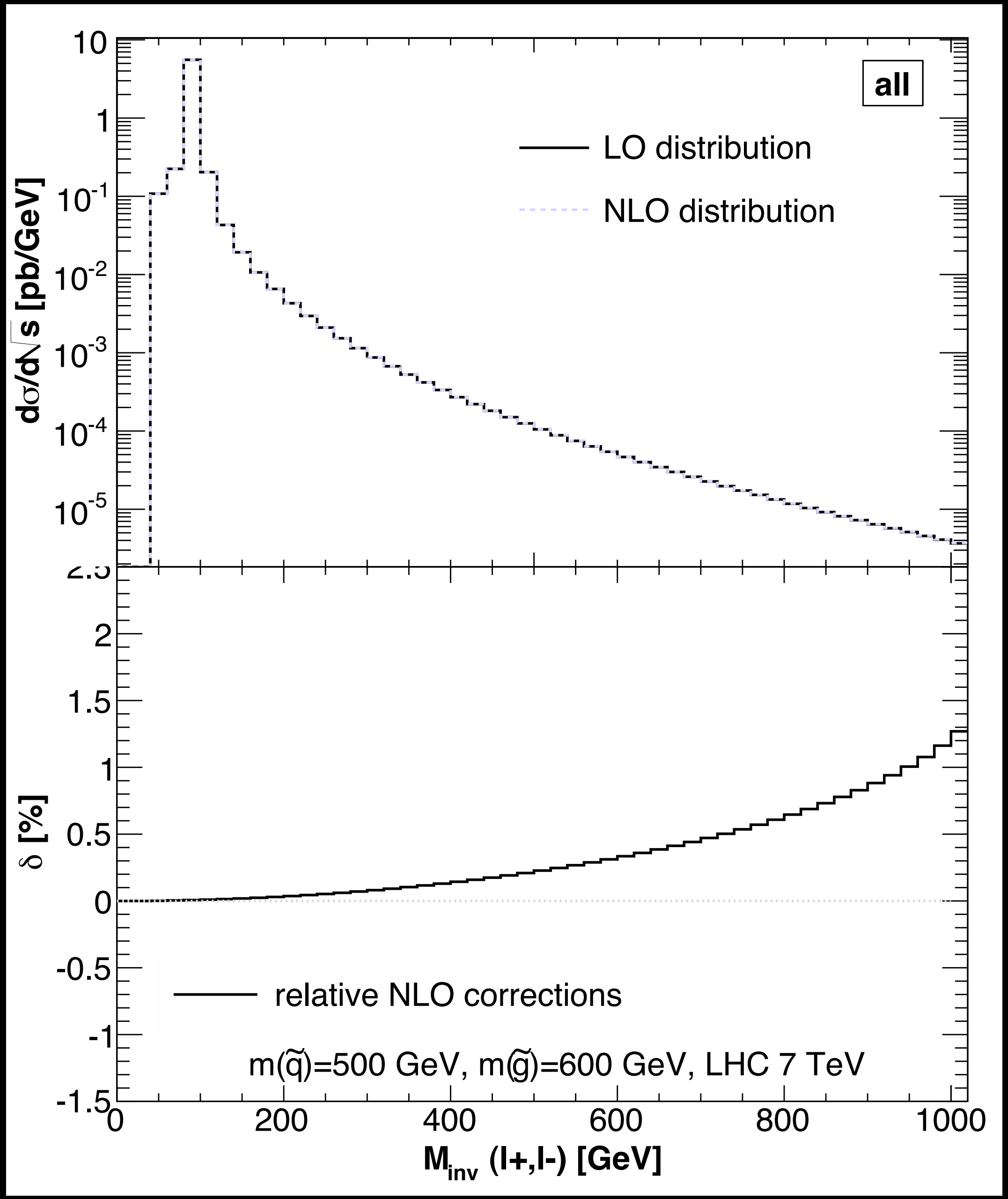


Jet p_T



Kinematic Distributions Preliminary

M_{ll}



Kinematic Distributions

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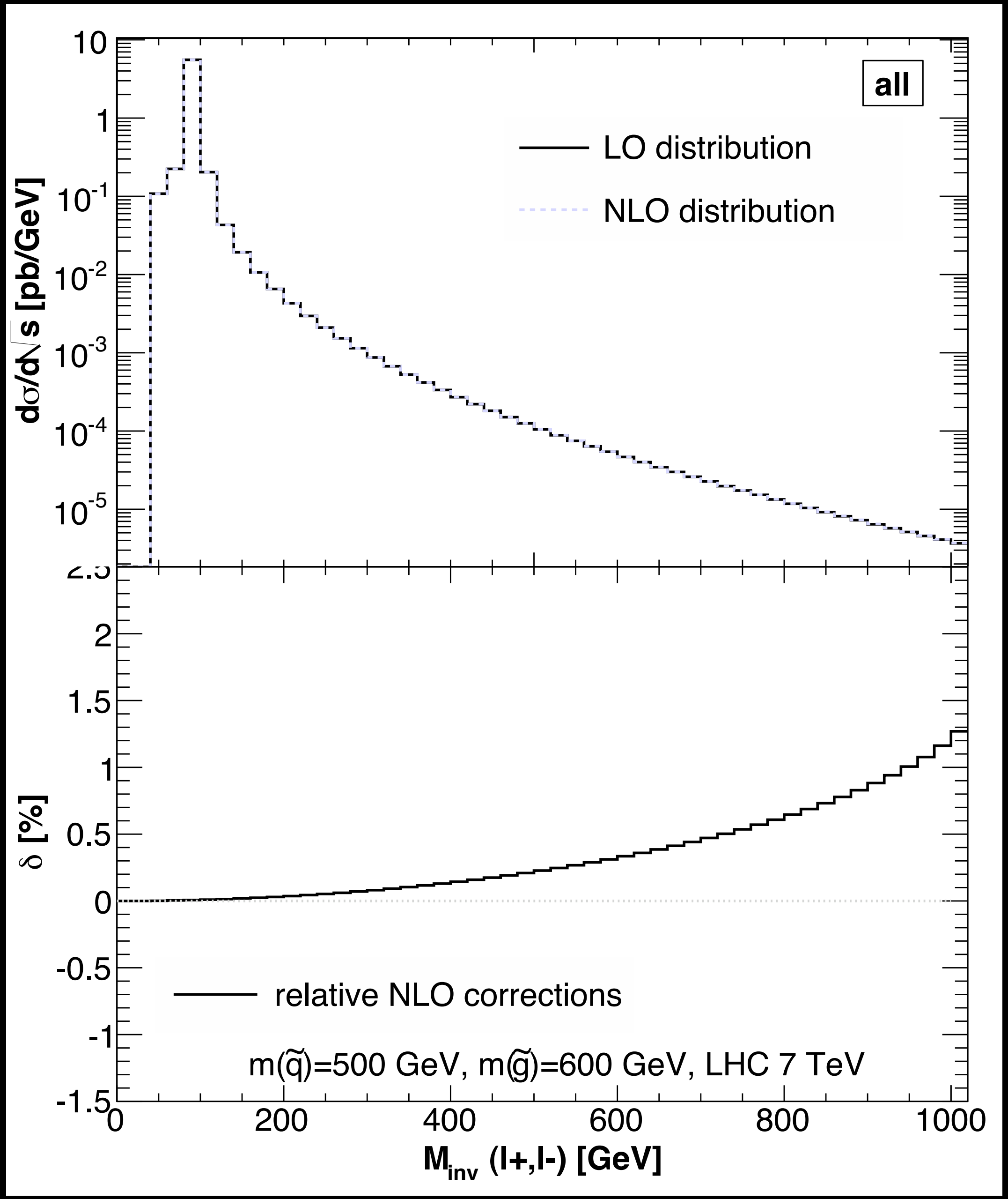
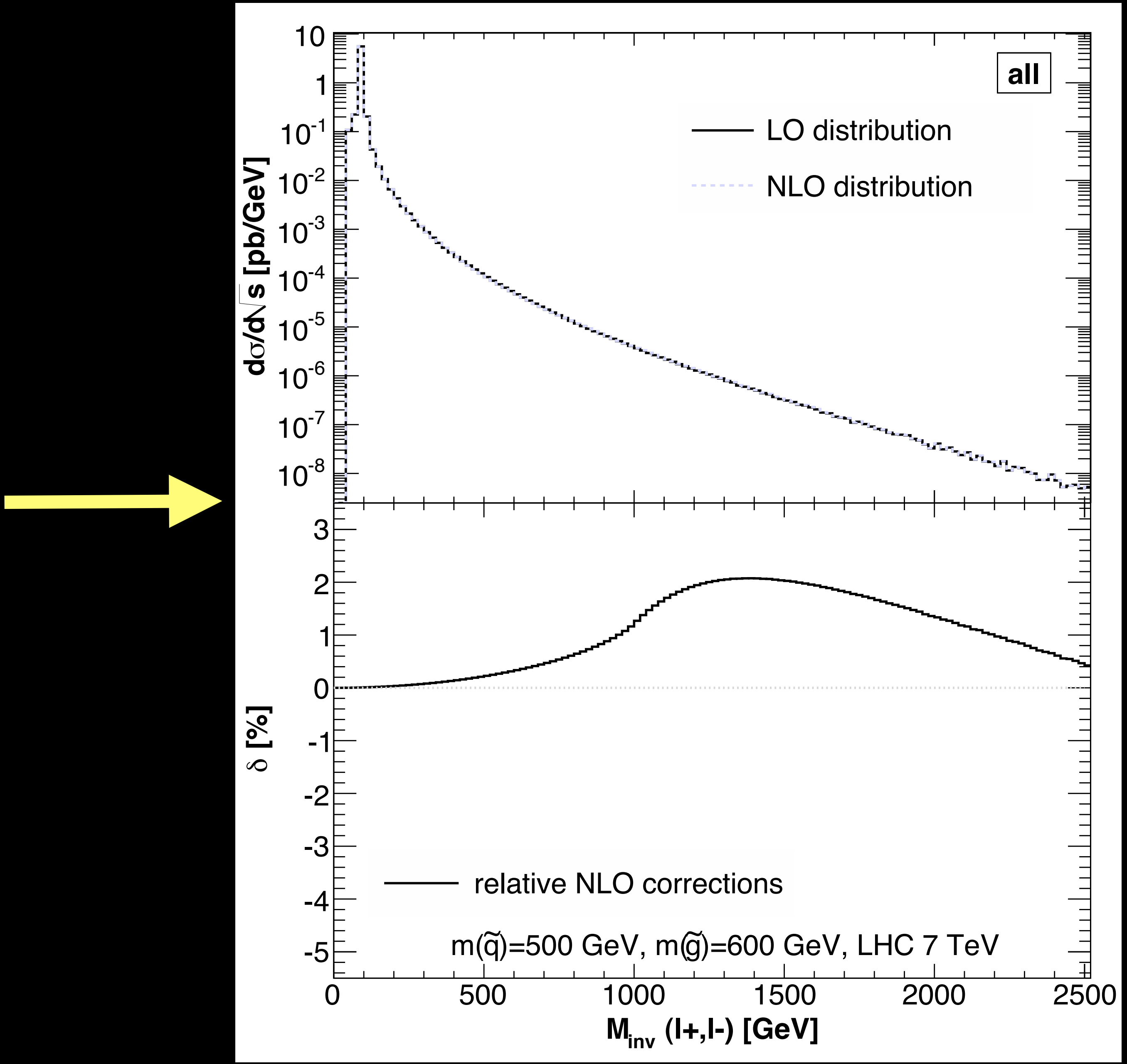
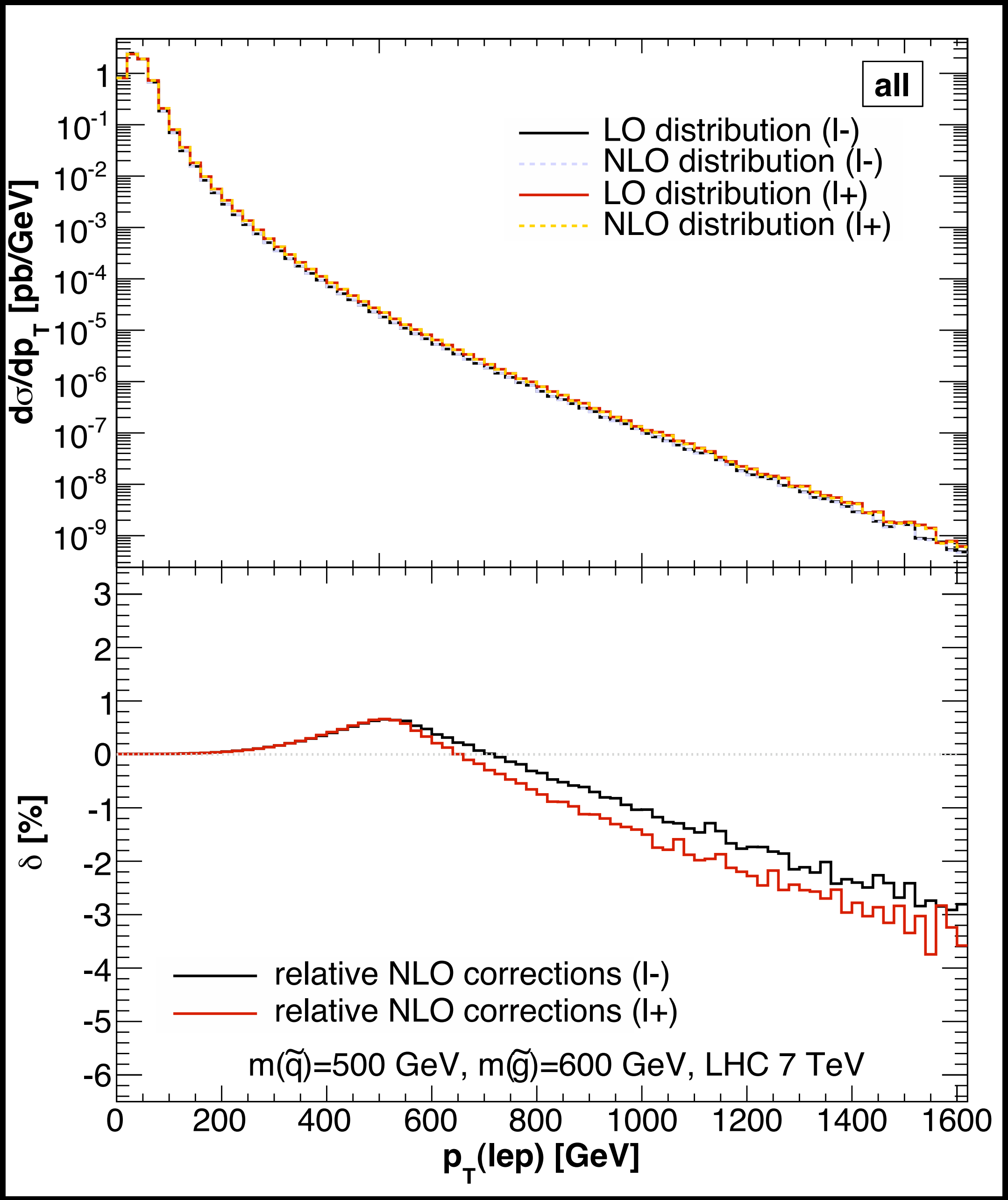




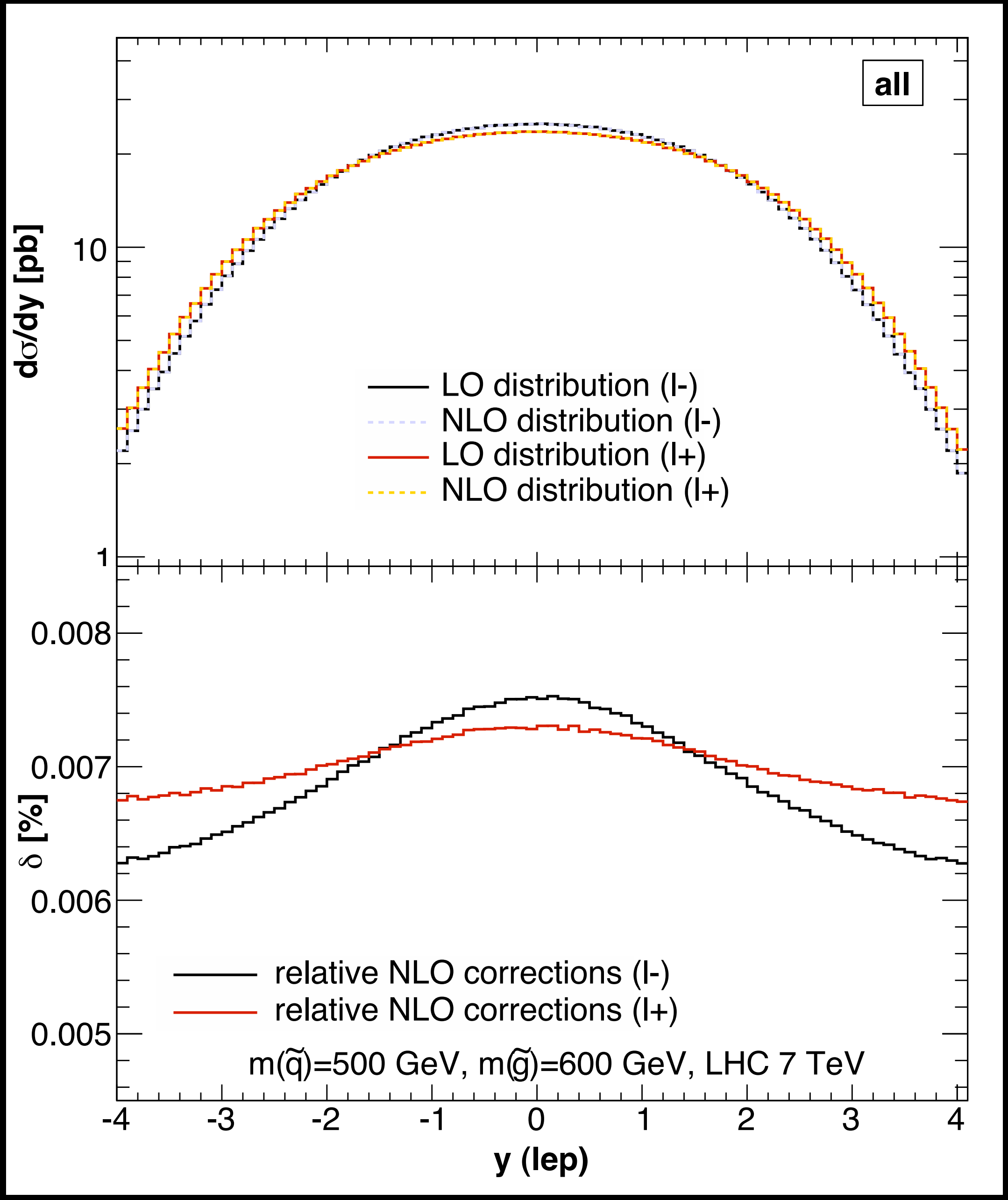
Kinematic Distributions

Preliminary

lepton p_T



lepton rapidity



Numerical Results

Preliminary

- Different squark and gluino masses?
- Suspect lower masses → greater contribution

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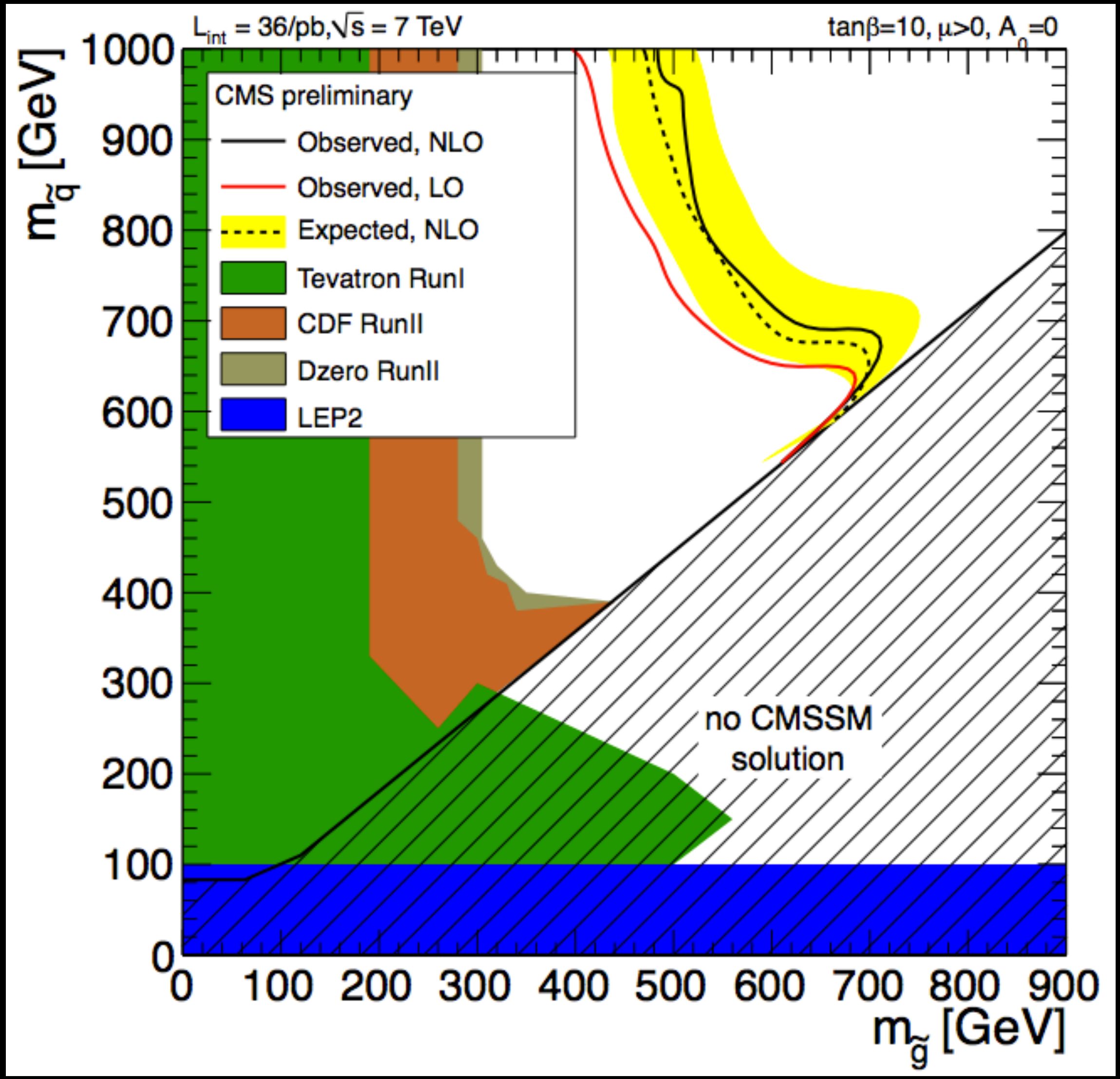
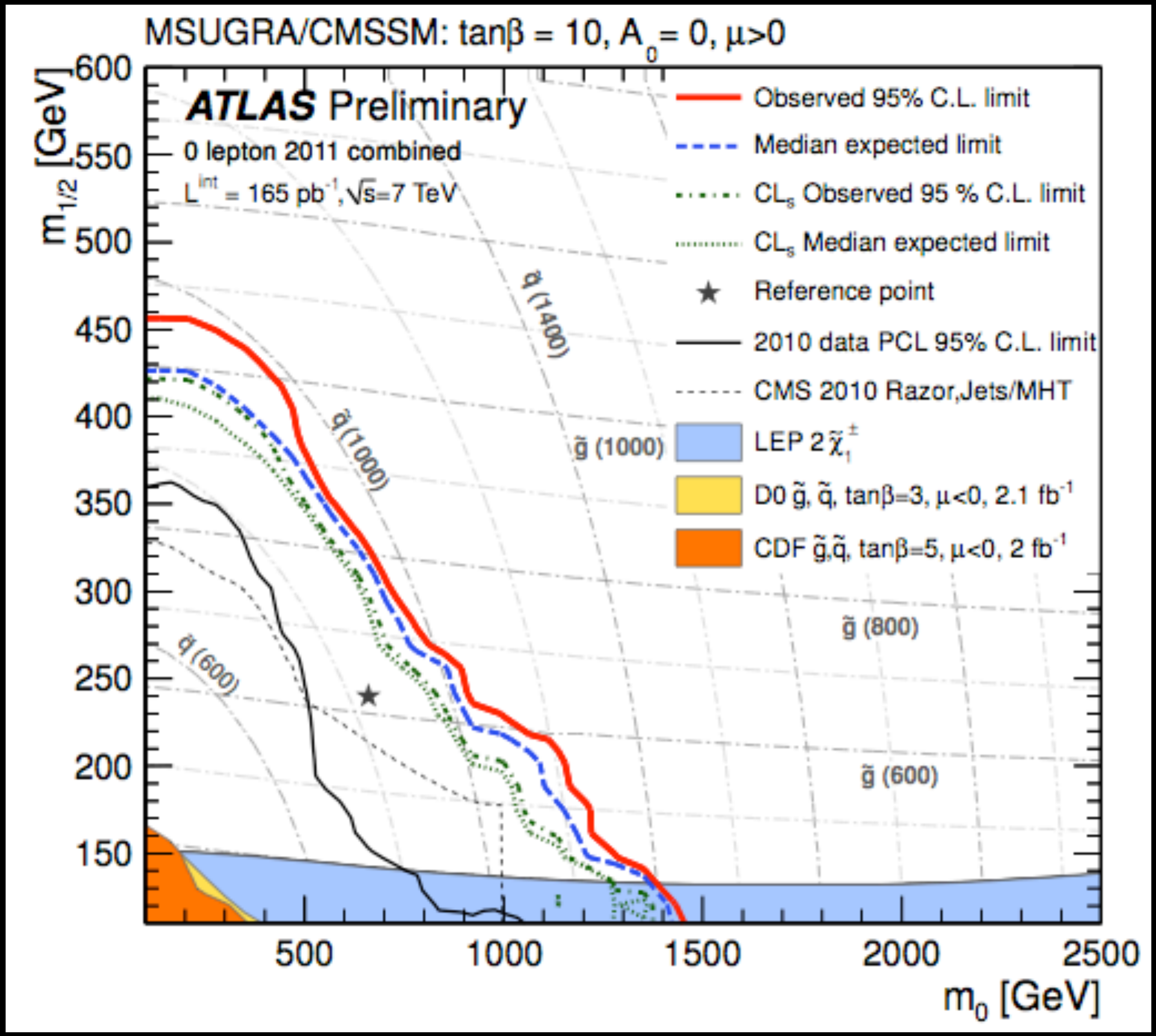
CMS PAS SUS-10-005



ATLAS-CONF-2011-086



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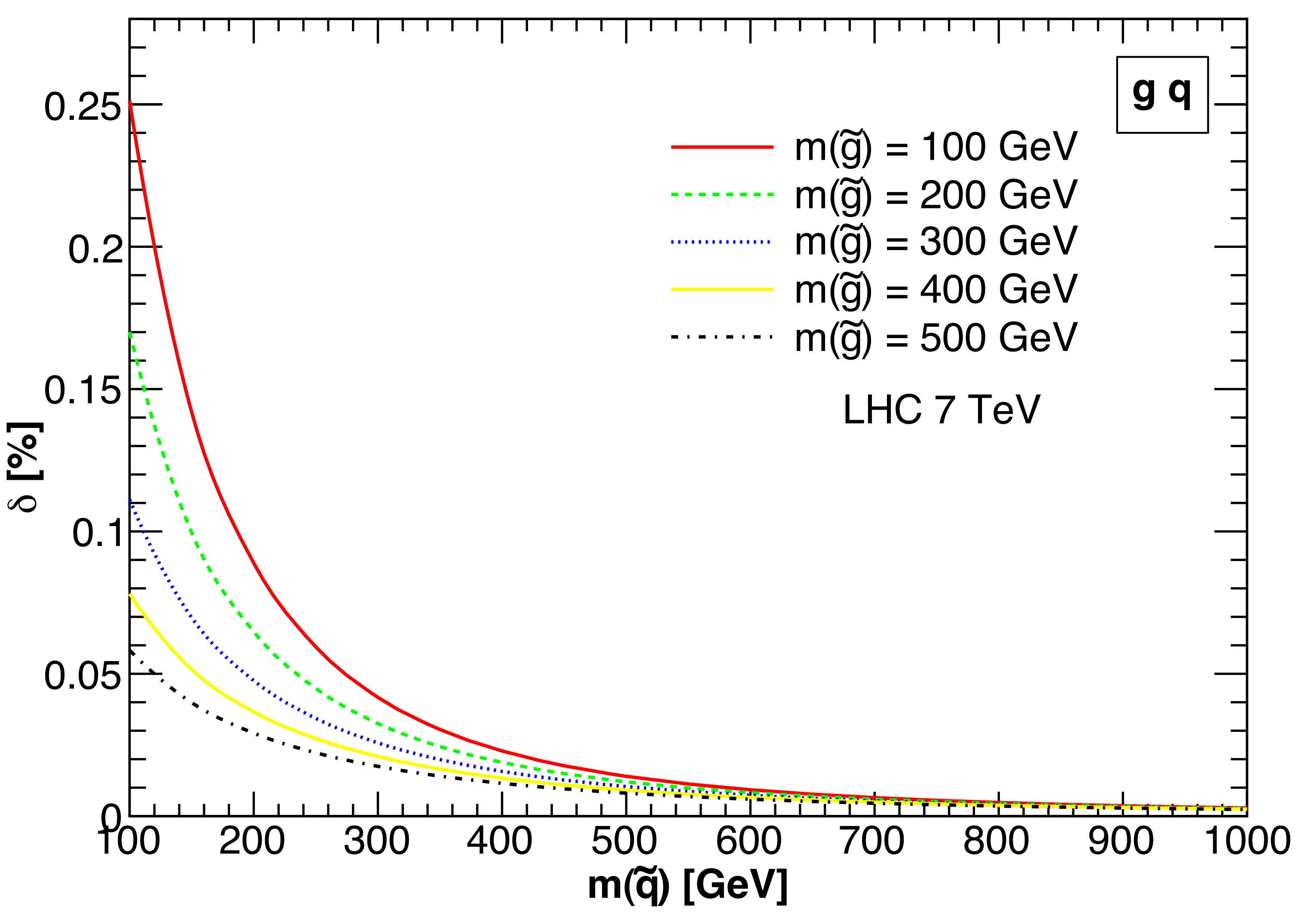

integrated cross section

gluon-quark channel only

Numerical Results

Preliminary

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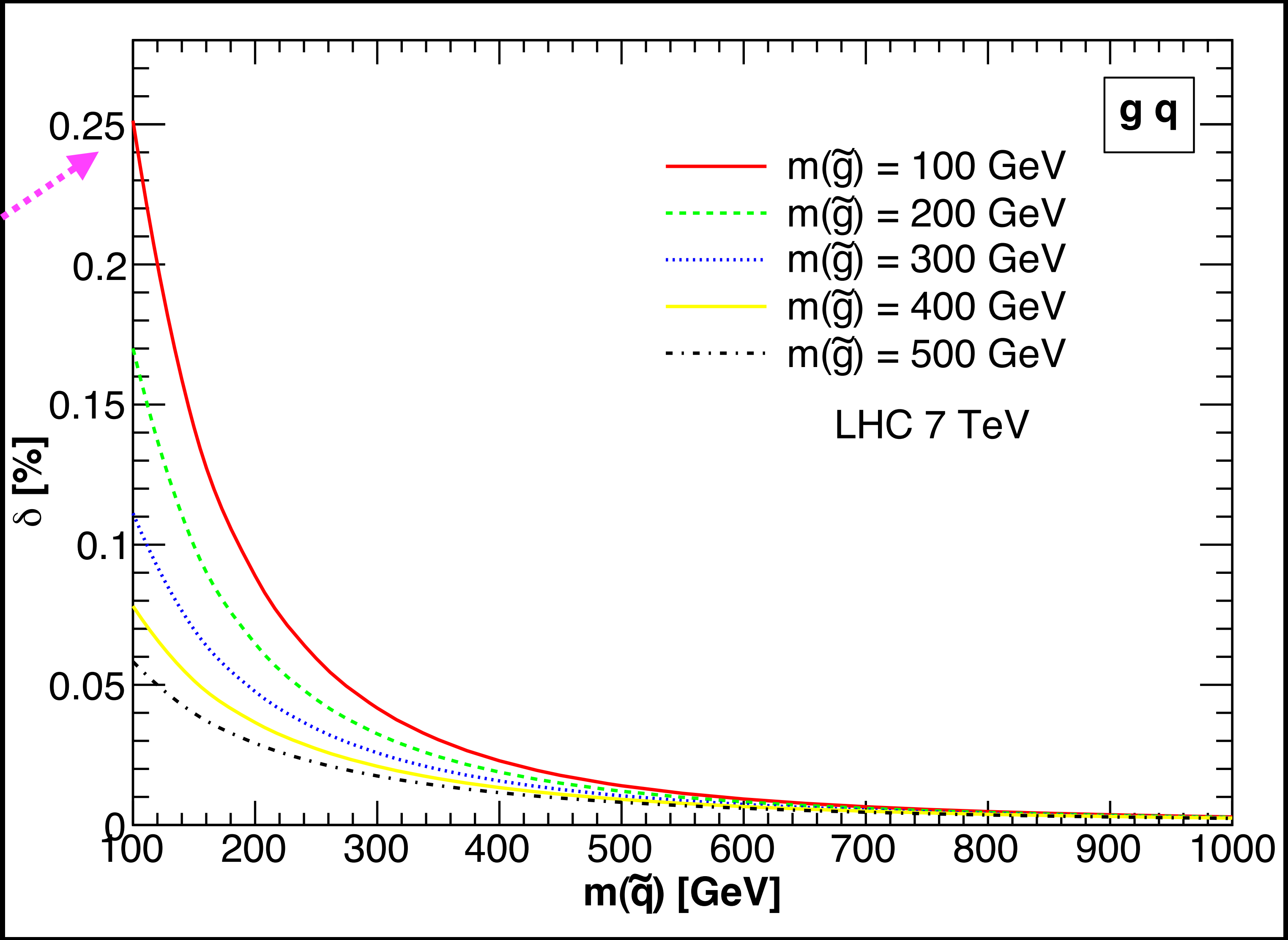
maximal ~0.25%



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Kinematic Distributions Preliminary

- Different masses, shift in kinematic distributions?
  - gluino mass = 350 GeV, squark mass = 400 GeV

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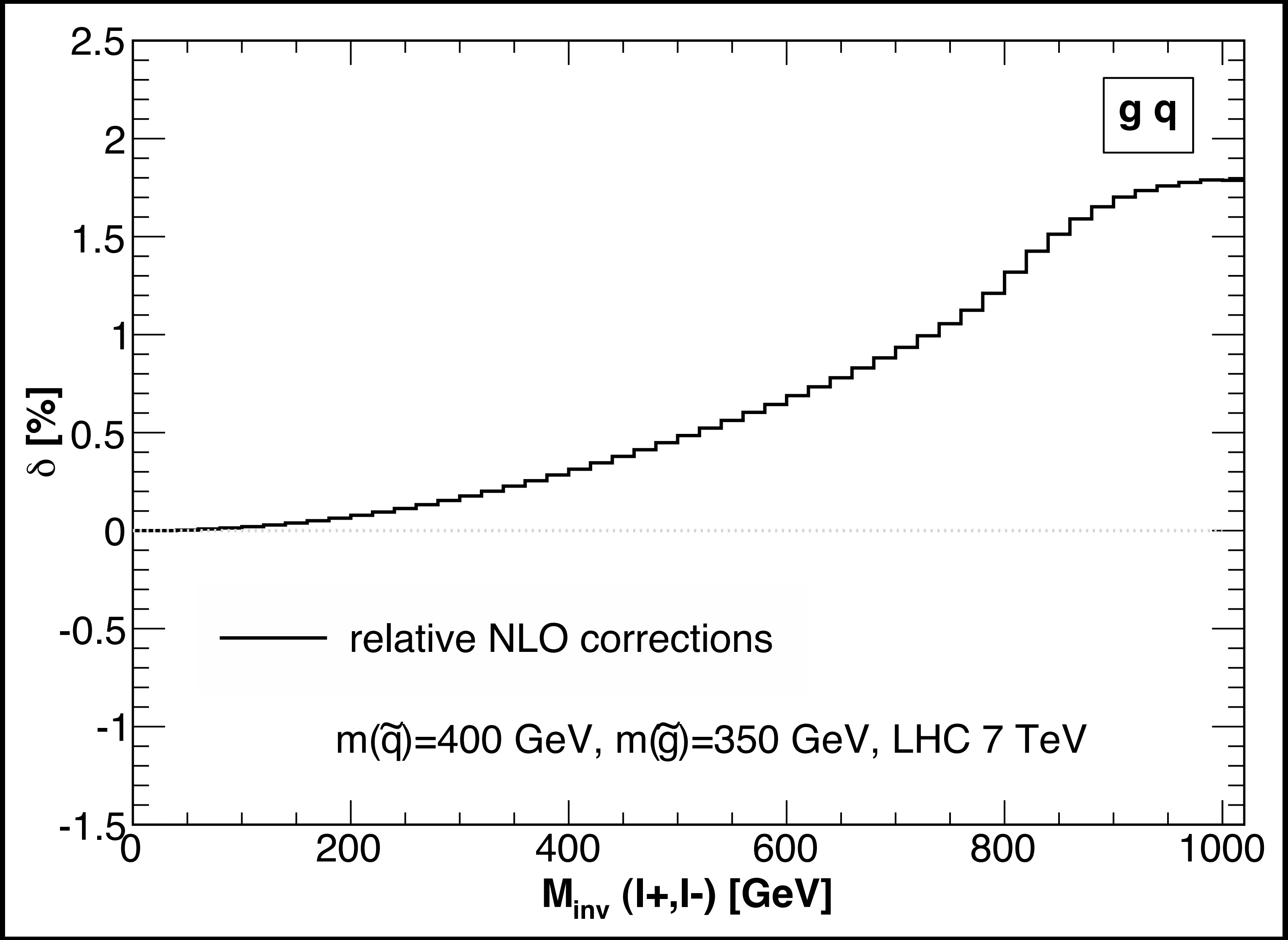
gluon-quark channel only



Kinematic Distributions

Preliminary

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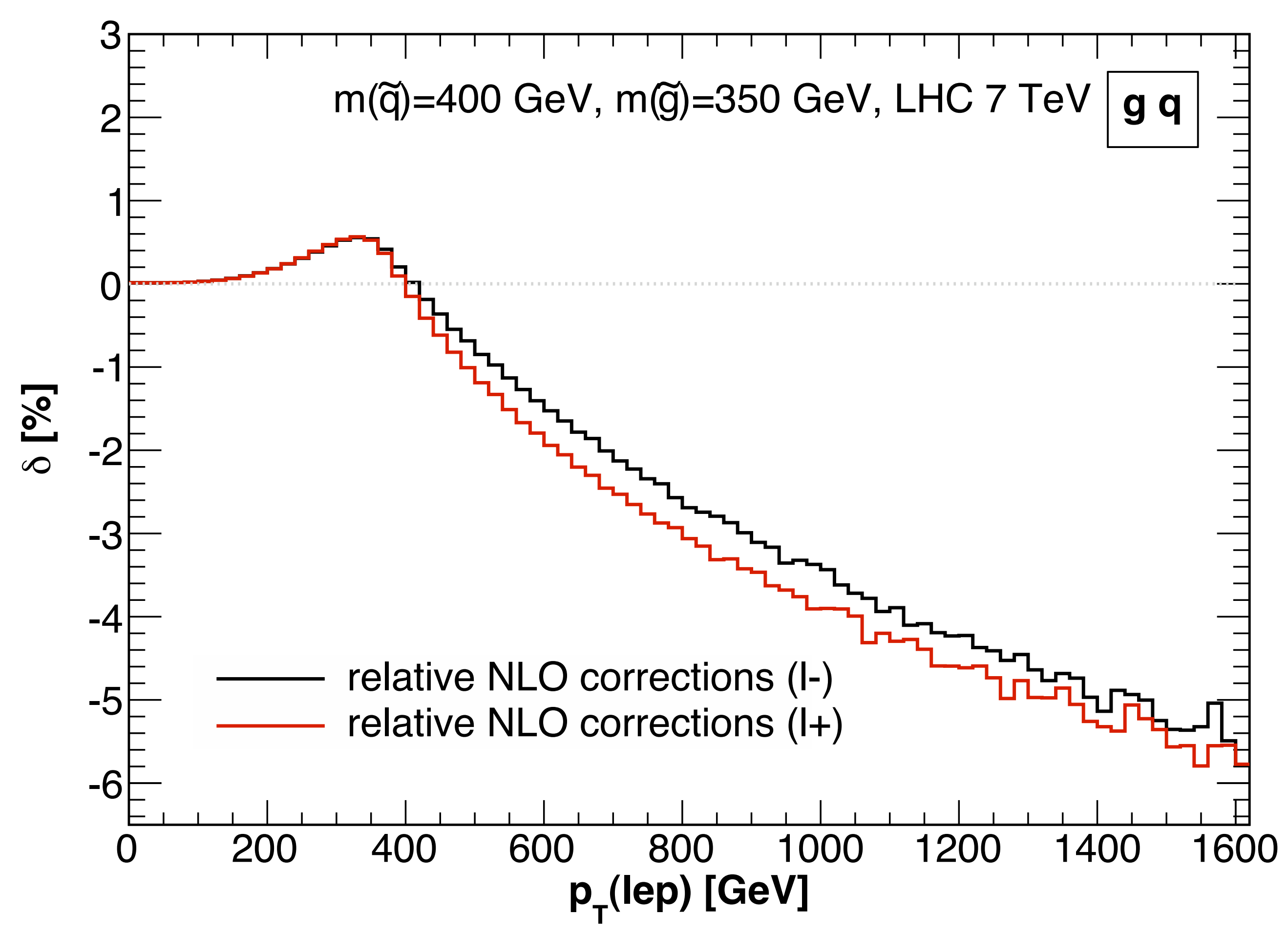
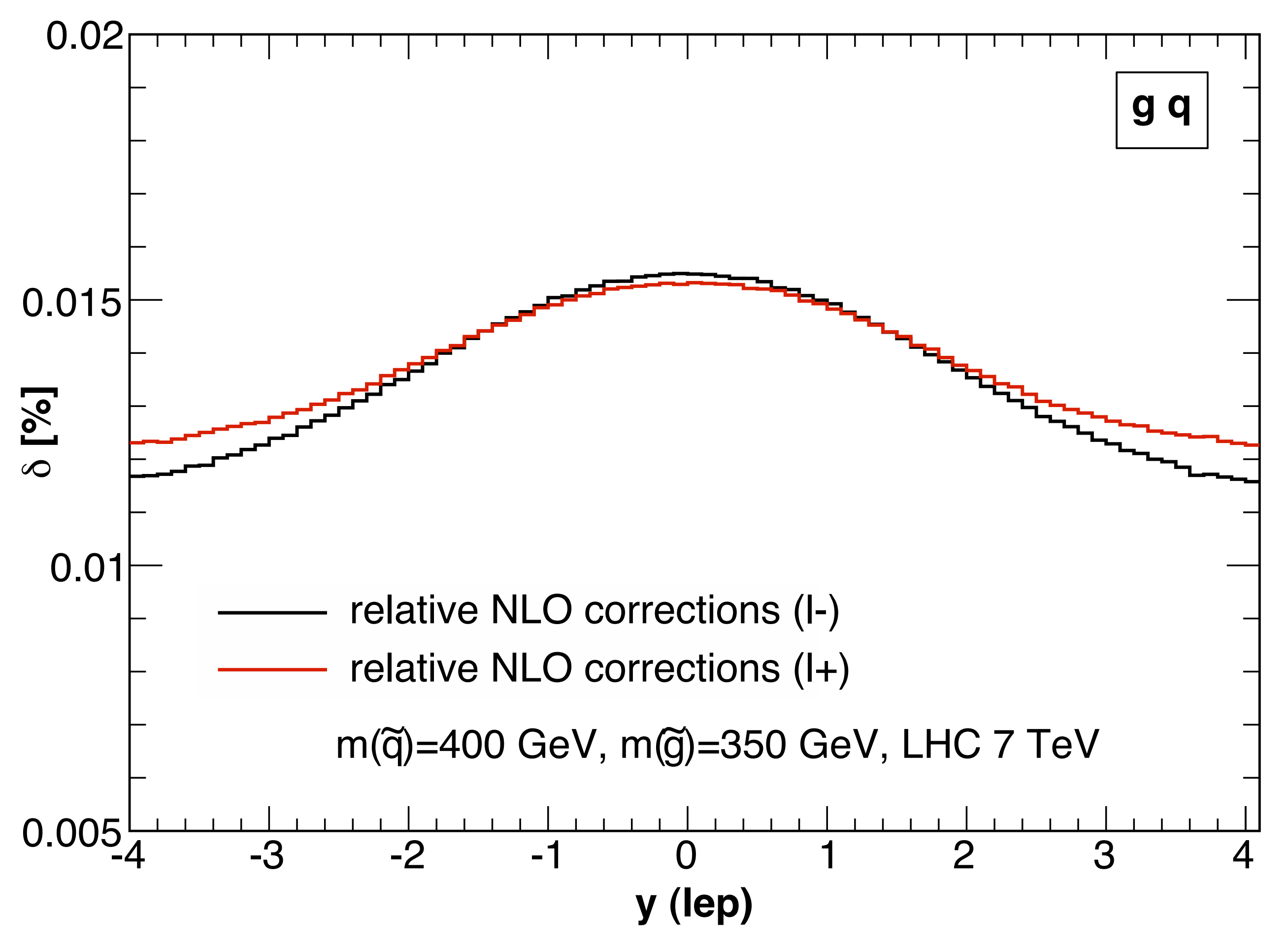
gluon-quark channel only





W+Jet Process

- W+jet production

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    - how do sQCD corrections effect this standard candle?

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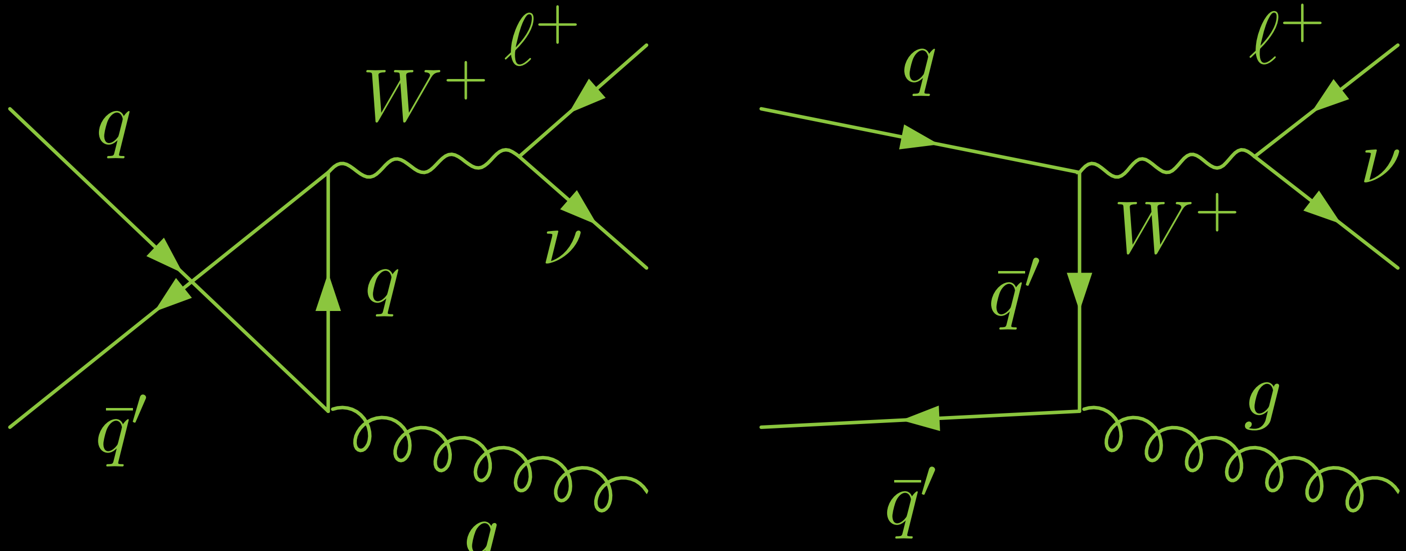
$\underline{q\bar{q}'}$:

+ quark-gluon channels



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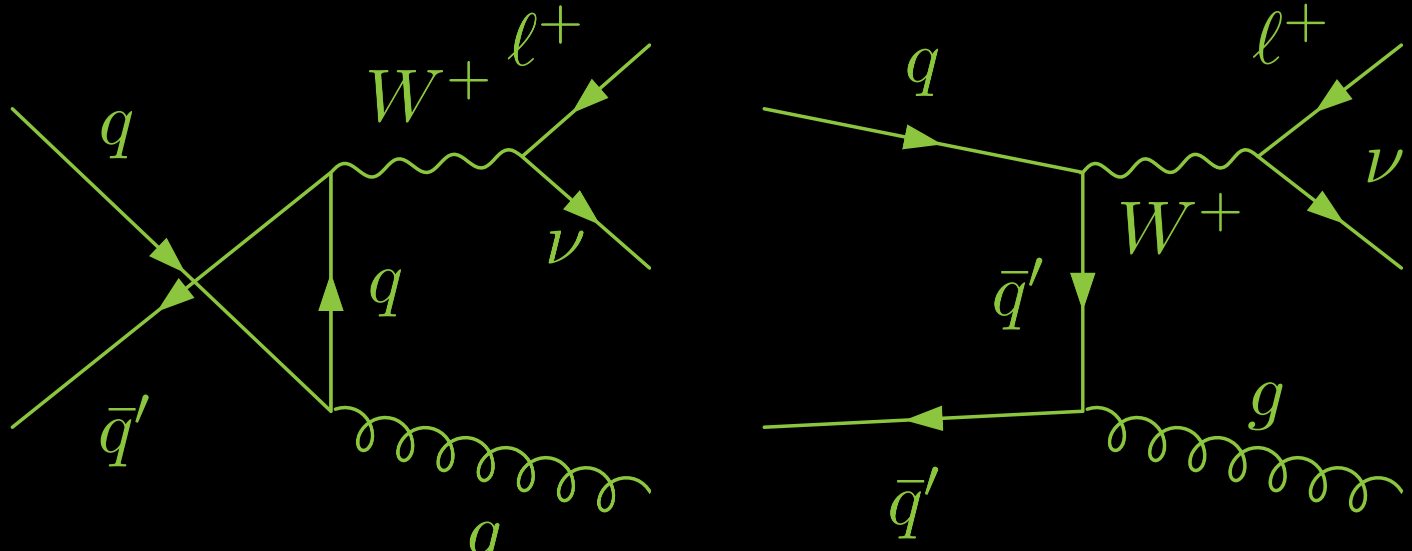

- same NLO structure: self-energy insertion, gluon and W vertex corrections, box terms

W+Jet Process

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  - how do sQCD corrections effect this standard candle?
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← only “left-handed” squarks contribute to W+jet with no L-R squark mixing

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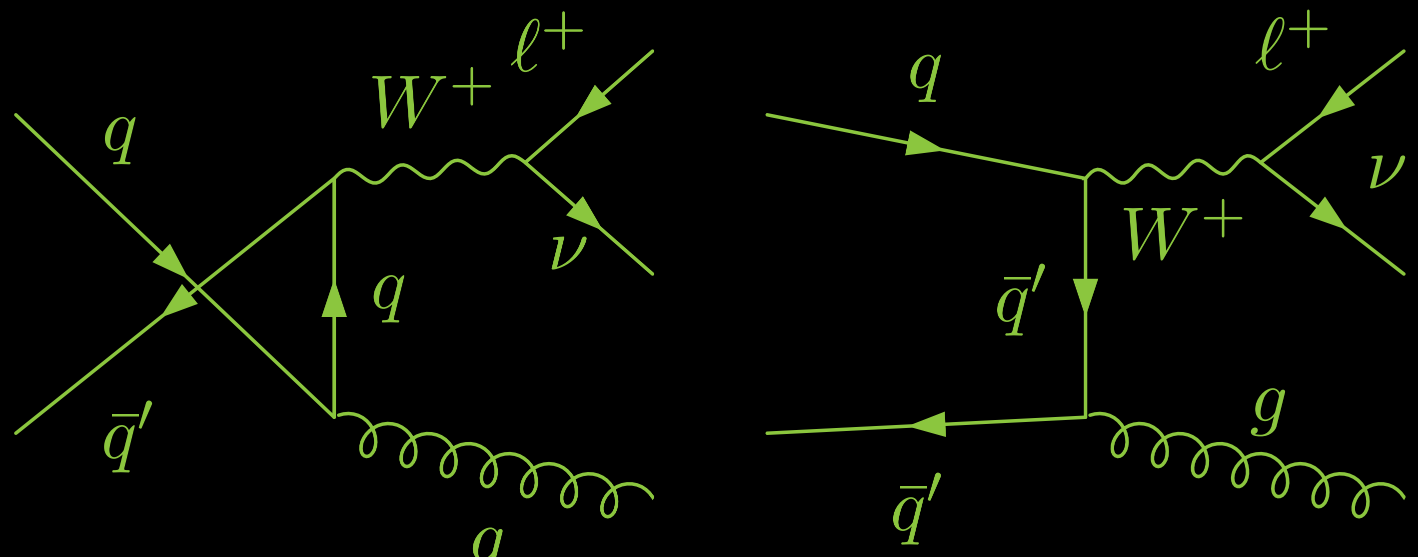

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Numerical Results

Preliminary

- $p_{T,jet} > 20$ GeV, $|\eta_{jet}| < 2.5$
- $p_{T,lep} > 25$ GeV, $E_{T,miss} > 25$ GeV
- CTEQ6M PDF set
- $\mu_R = \mu_F = M_W$

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$\sqrt{s} = 7$ TeV

$\sigma_{all,int} = 635.94$ pb

all = W^+ & W^-

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sQCD corr = 36.94 fb

$\delta rel = 0.006\%$

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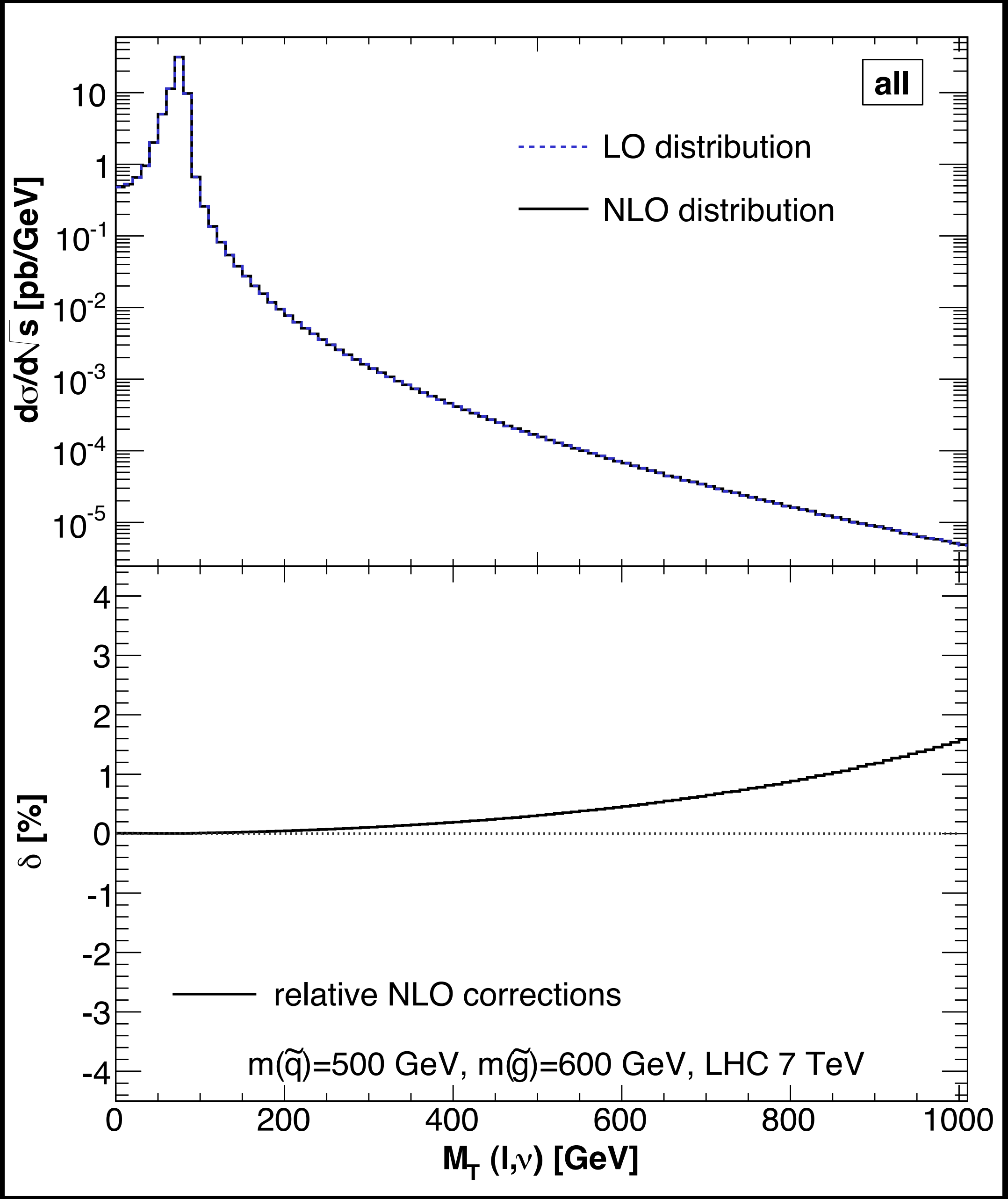
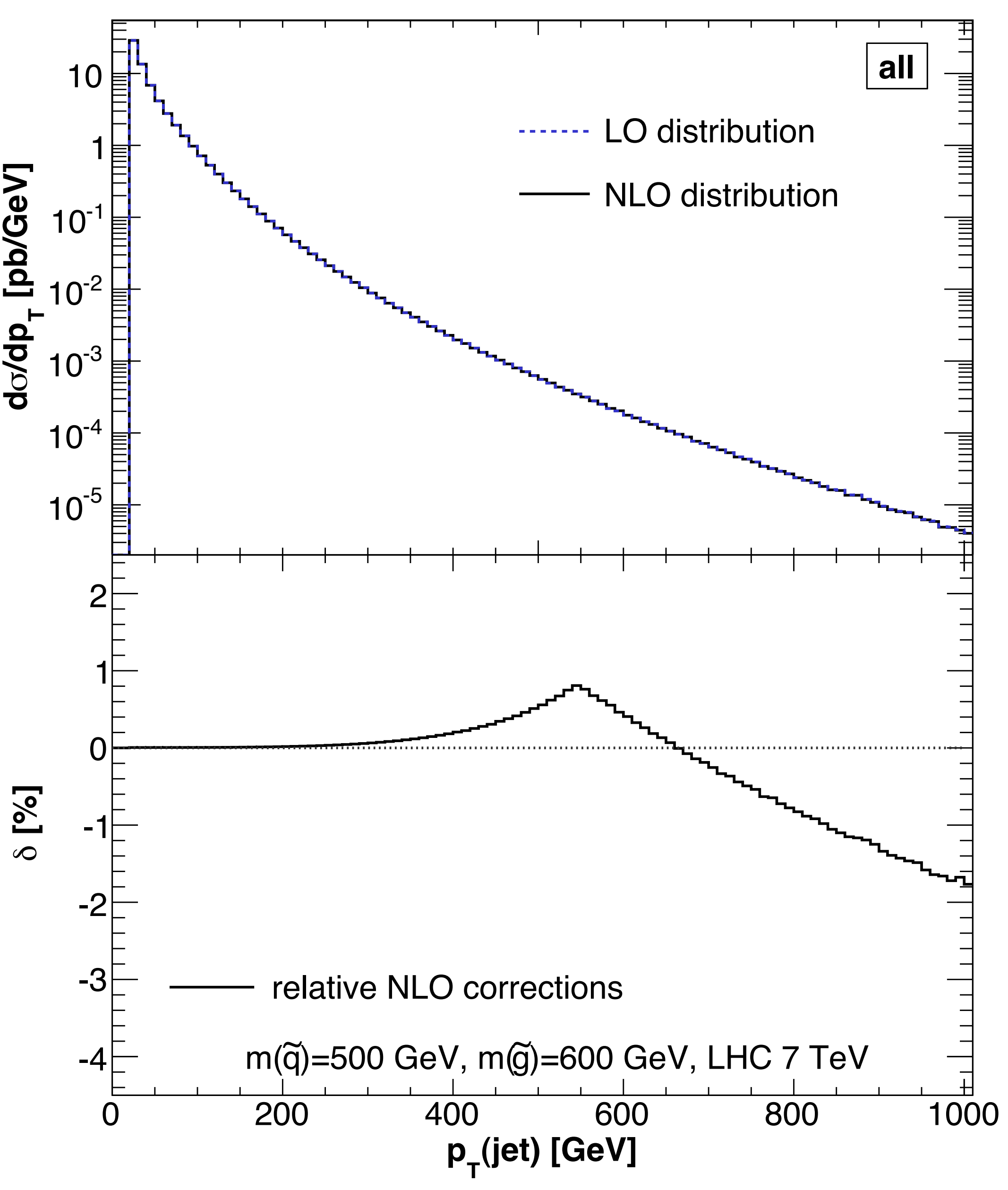
Kinematic Distributions

Preliminary

M_T



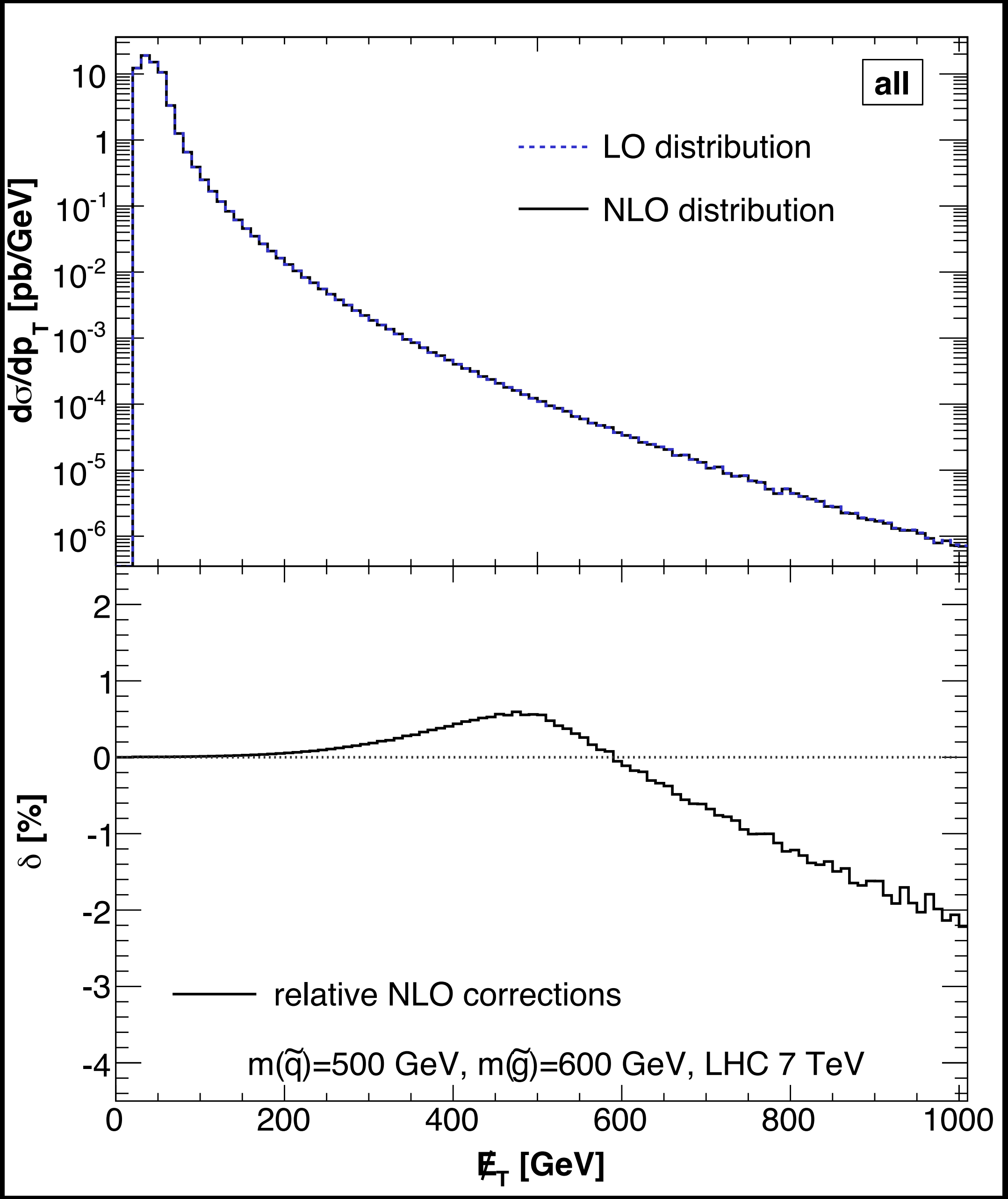
Jet p_T



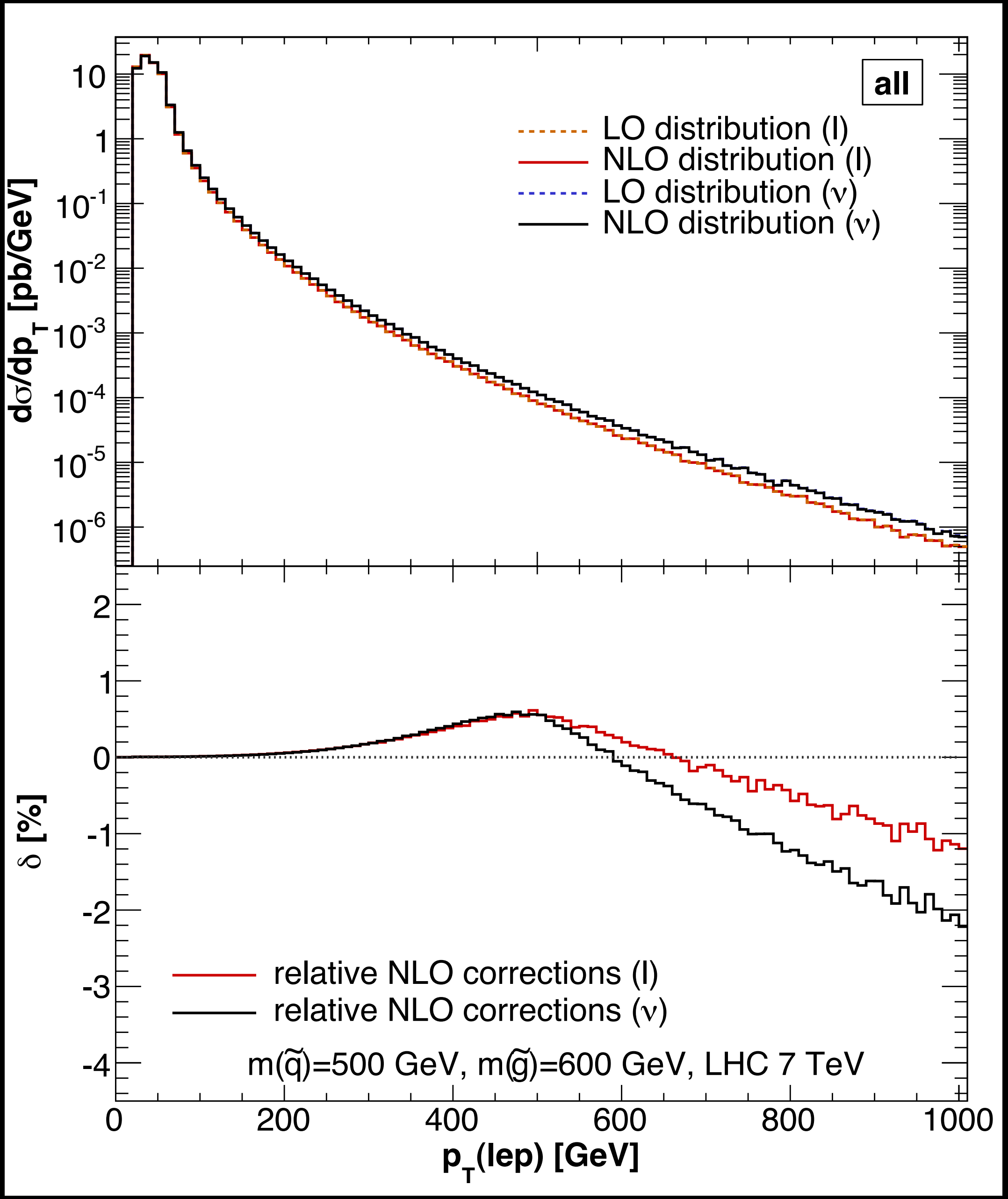
Kinematic Distributions

Preliminary

$E_{T,\mathrm{miss}}$ p_T



lepton p_T



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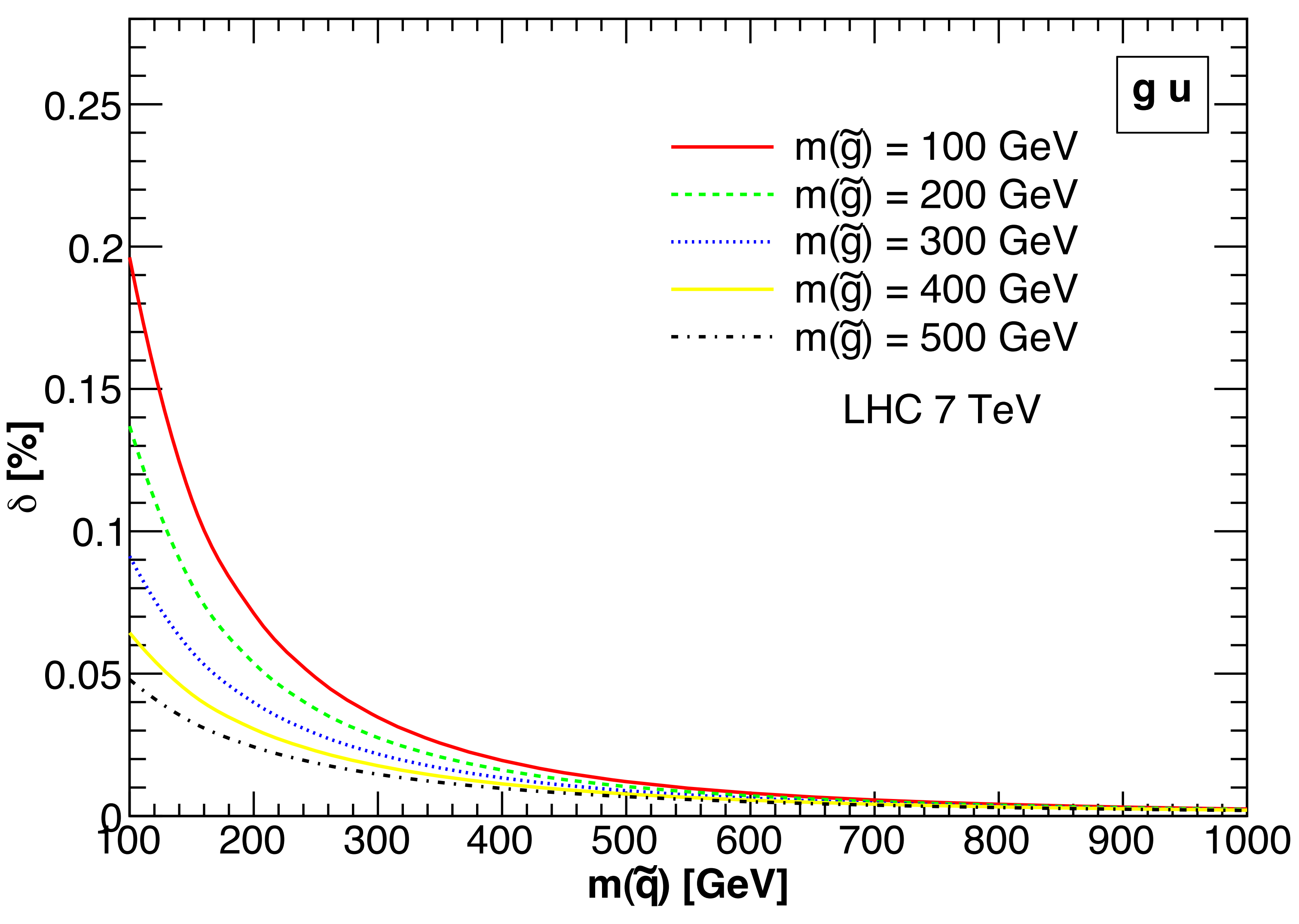

integrated cross section

gluon-quark channel only

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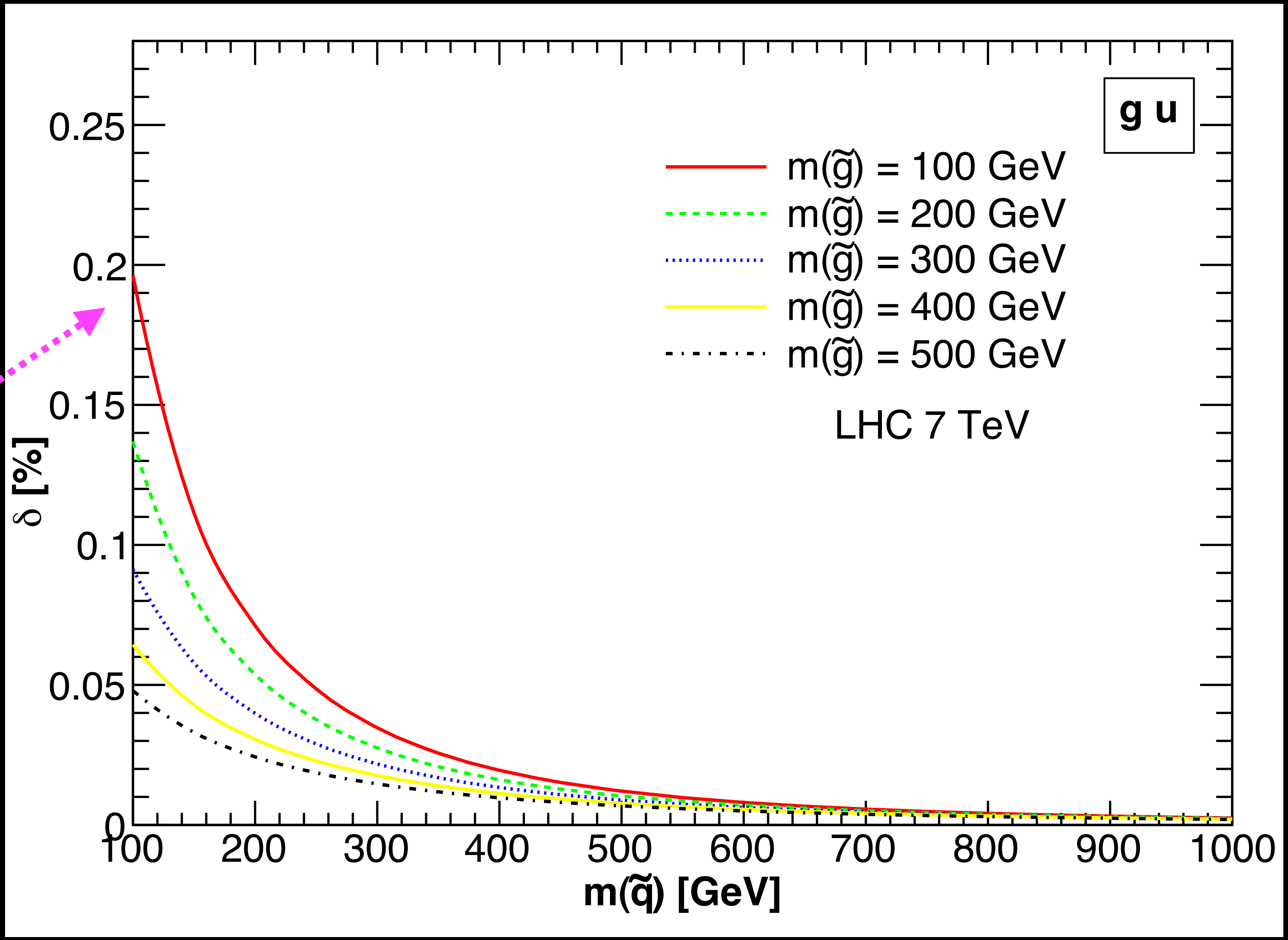

integrated cross section

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maximal ~0.20%

sQCD to Drell-Yan

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- Drell-Yan at NLO in sQCD preformed previously (no jet)

sQCD to Drell-Yan

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  - neutral current arXiv:0911.2329
    - low invariant mass range: ~0.1% high (TeV): ~1-2%

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  - charged current arXiv:0710.3309
    - low invariant mass range: <0.1% high (TeV): ~1%

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    - low invariant mass range: ~0.1% high (TeV): ~1-2%
  - charged current arXiv:0710.3309
    - low invariant mass range: <0.1% high (TeV): ~1%
- W/Z + jet production at NLO in sQCD is in good agreement with DY scenario

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