Theory @ Fermilab: A Lightning* Survey

Gordan Krnjaic

Fermilab

Patrick Fox, Bogdan Dobrescu, Dan Hooper, Christopher Hill, Roni Harnik, Marcela Carena, Andreas Kronfeld, Stephen Parke, Paul Mackenzie, Ruth Van de Water, John Campbell, Chris Quigg, Scott Dodelson, Albert Stebbins, Walter Giele, Estia Eichten, William Bardeen, Kiel Howe, John Kearney, Elise Jennings, Ishrad Mohammed, Pilar Coloma, Ran Zhou, Ye Li, Seyda Ipek, Aarti Raghuraman, Zhen Liu

New Perspectives 2016

*hopelessly inadequate & incomplete

Outstanding Problems in Fundamental Physics

Identity of dark matter

Matter asymmetry

Nature of EWSB

Neutrino masses, mixings, interactions

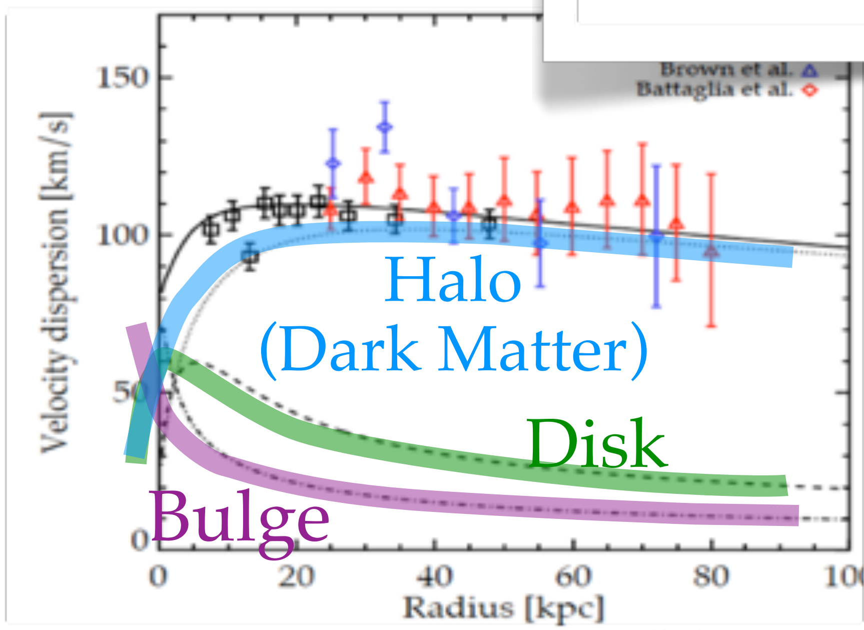
Flavor puzzle (CKM structure)

Strong CP problem

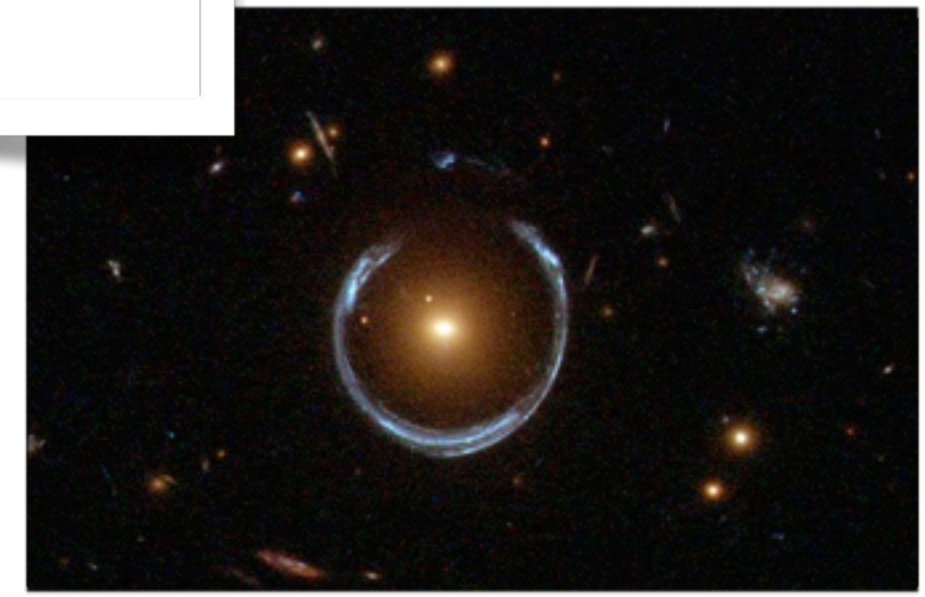
How to make progress?

new models + new searches + better calculations

Dark Matter

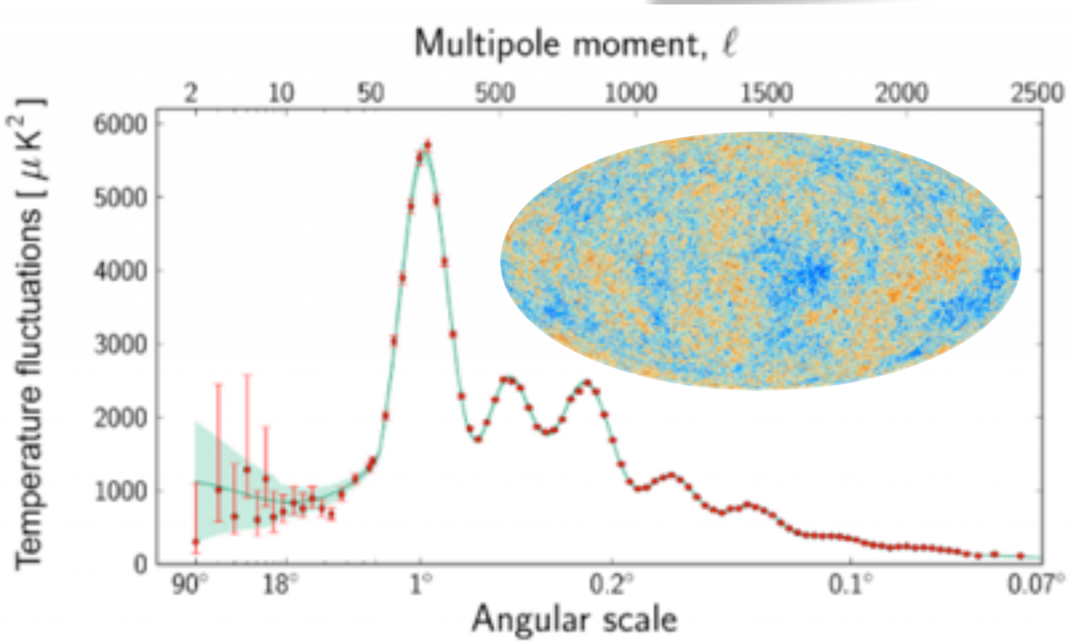


Rotation Curves

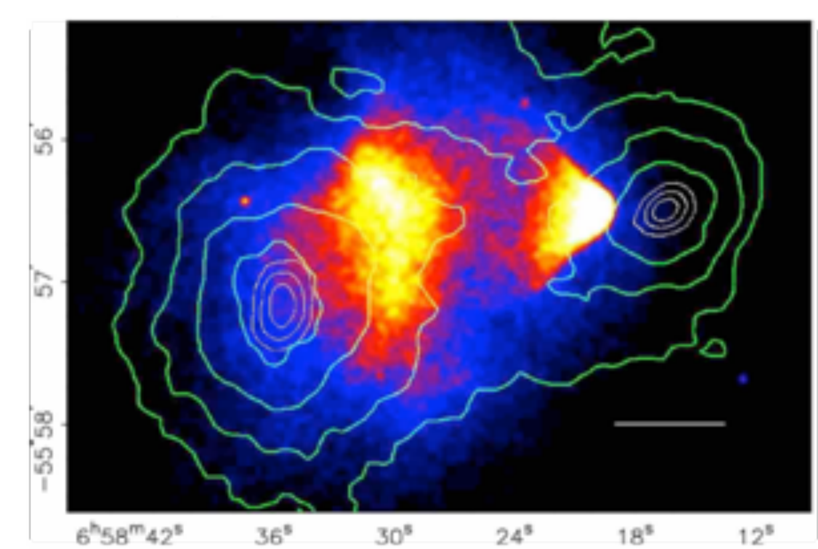


Gravitational lensing

CMB



Cluster collisions



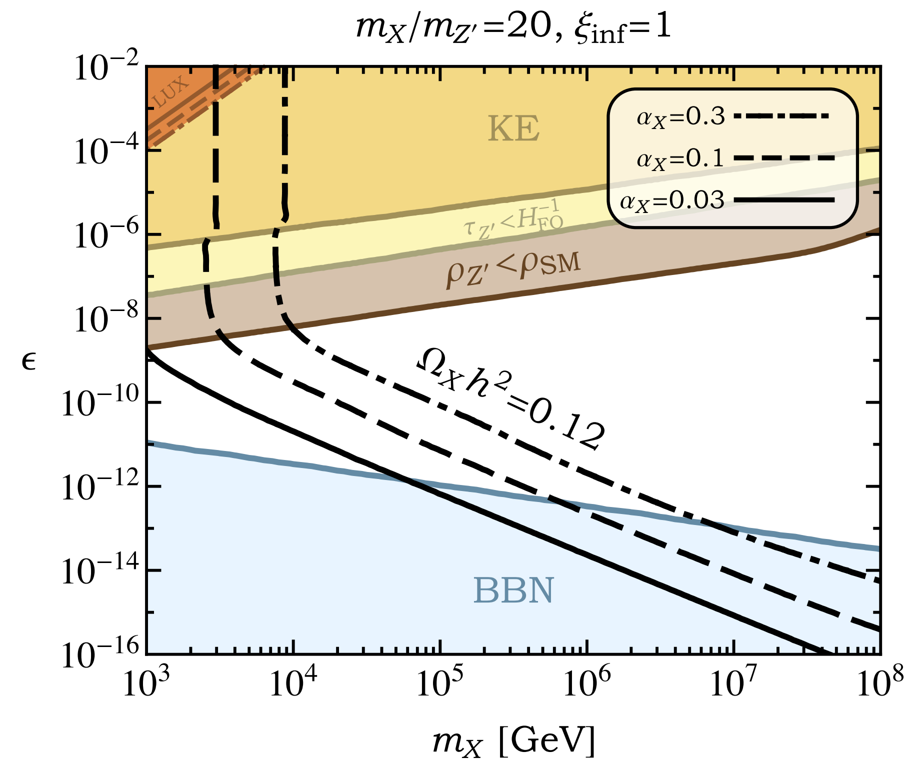
What is its particle nature?
How to discover it?

DM Model Building

PeV scale thermal DM from decoupled hidden sector

Extends viable thermal DM mass range

Asher Berlin, **Dan Hooper, GK**
arXiv: 1602.08490

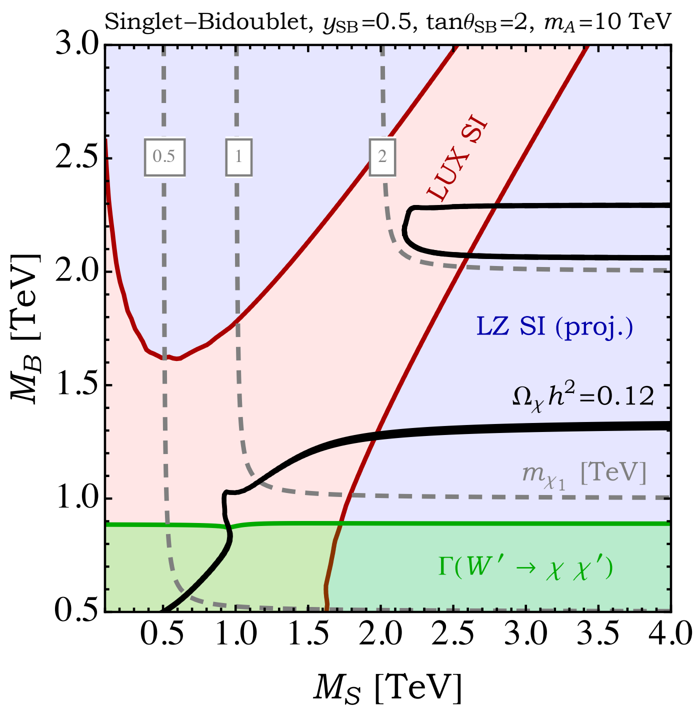


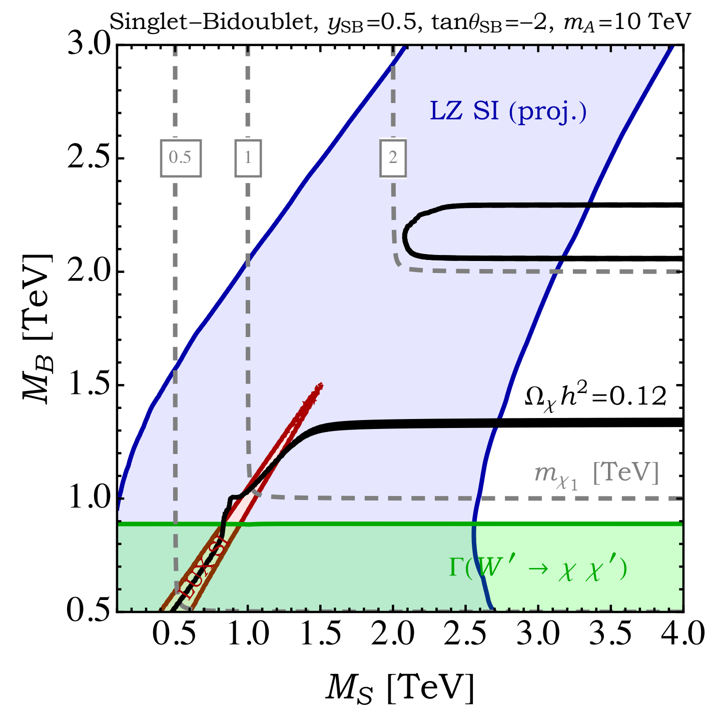
Mixed DM in L/R symmetric models

Full treatment neutral state mixing

Connection to LHC diboson excess

Asher Berlin, **Patrick "Paddy" Fox, Dan Hooper, Gopolang "Gopi" Mohlabeng**
arXiv: 1602.08490





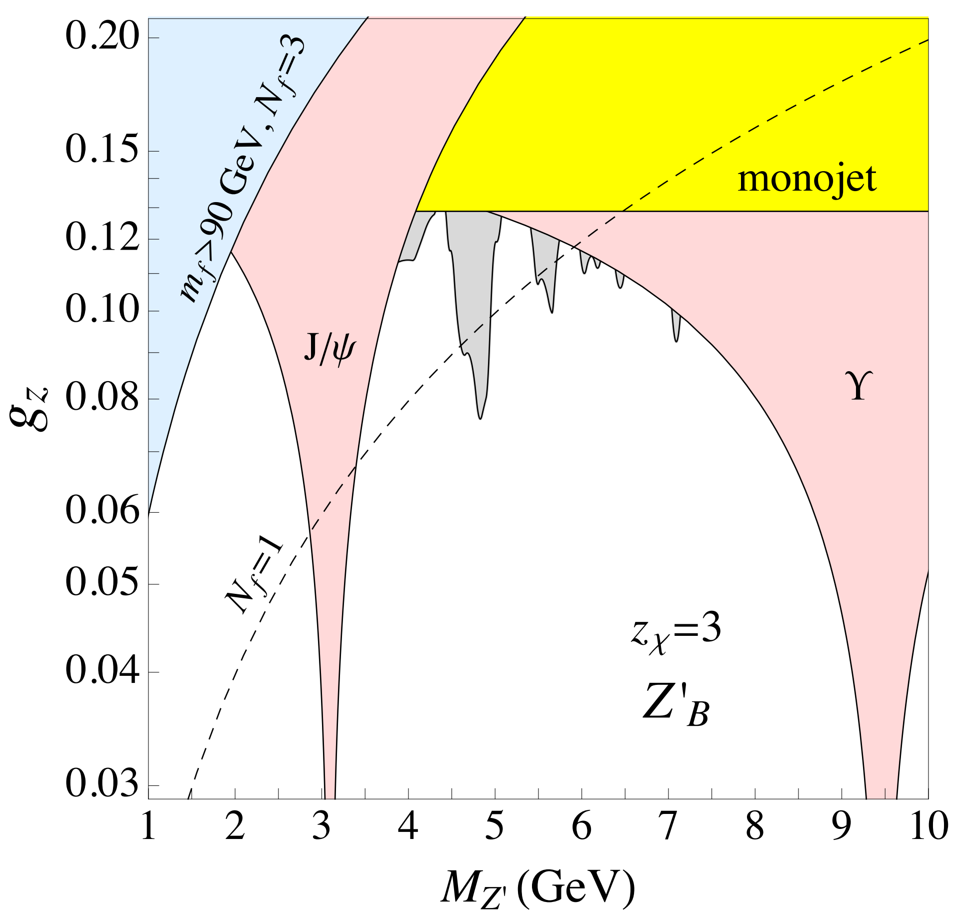
New DM Searches

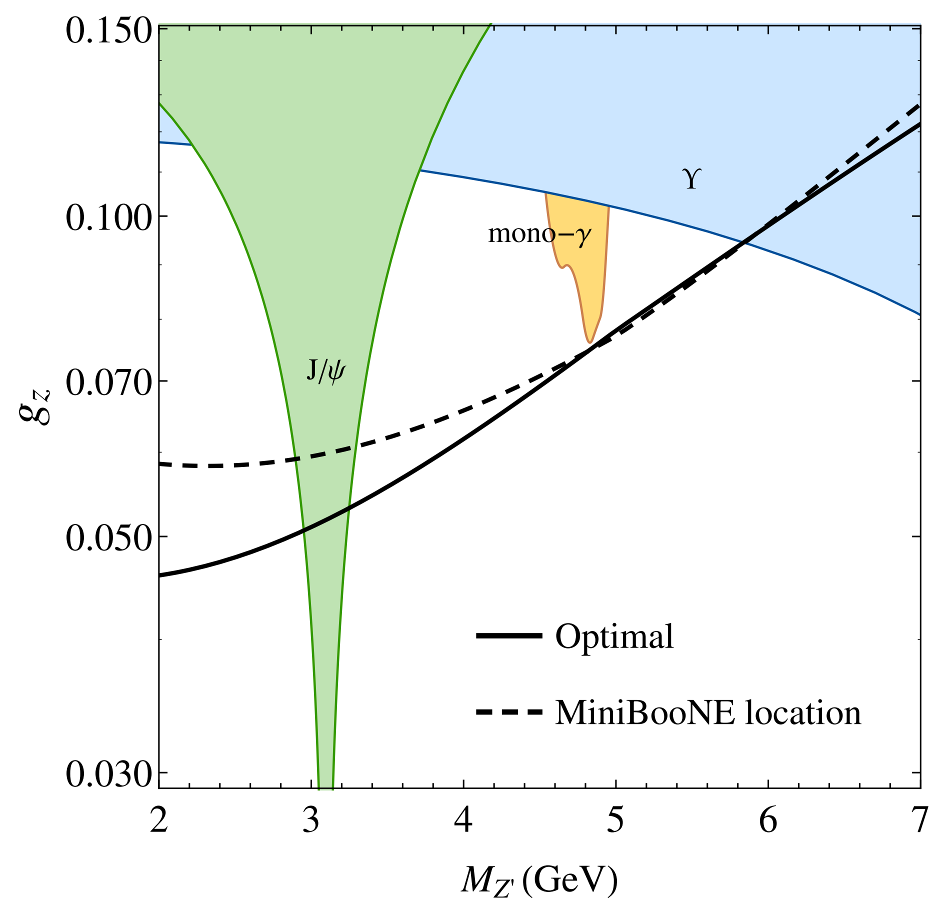
Light DM: production in Main Injector, scattering at NOυA

Bogdan Dobrescu, Claudia Frugiuele arXiv: 1401.1566

Light DM beam @ LBNF

Pilar Coloma, Bogdan Dobrescu, Claudia Frugiuele, Roni Harnik
arXiv: 1512.03852

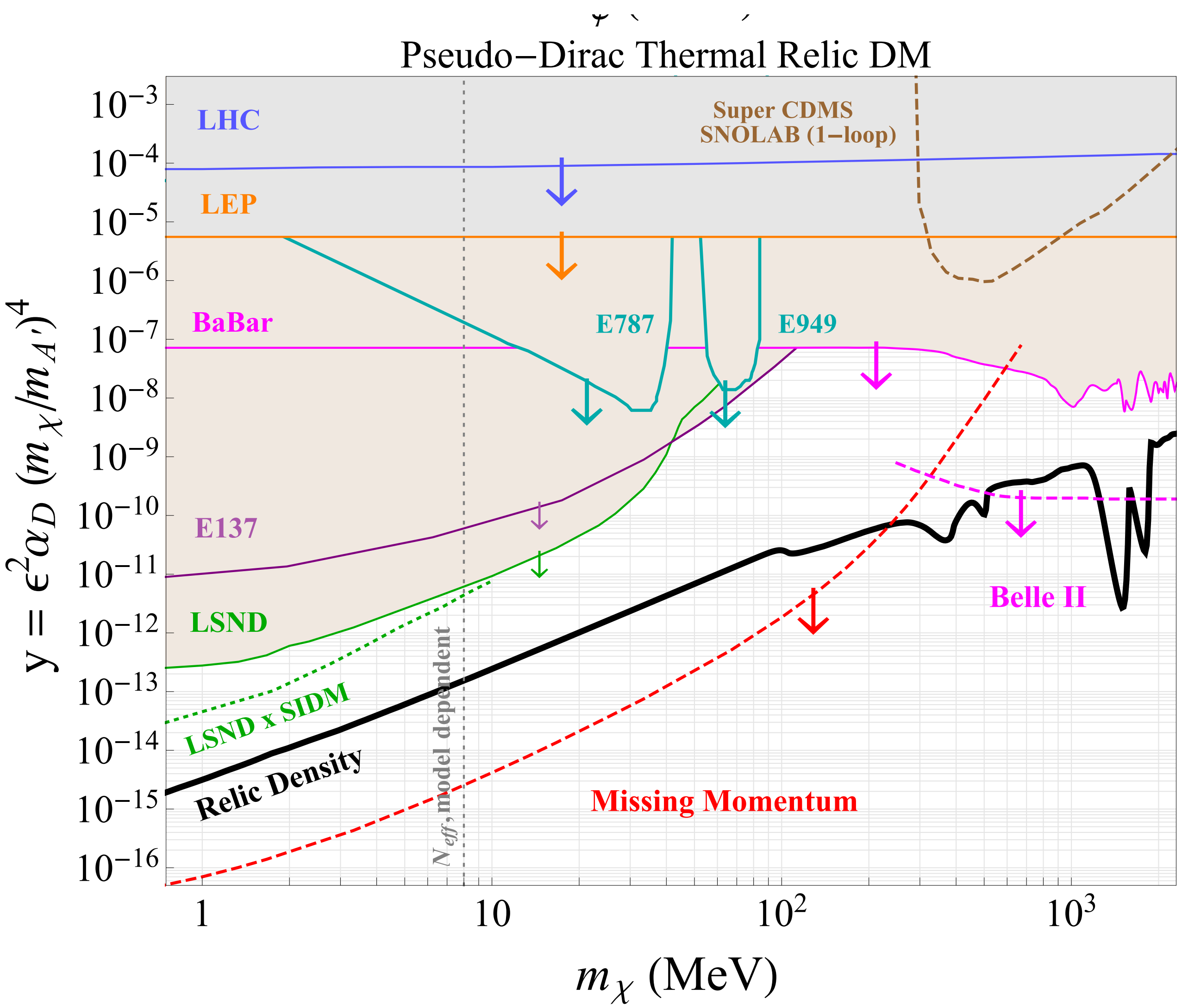


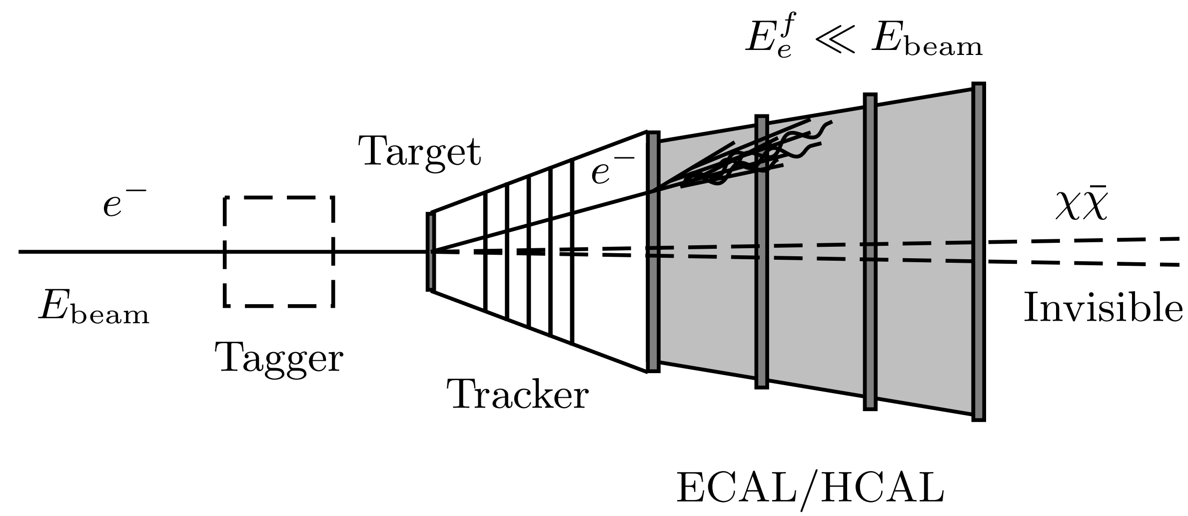


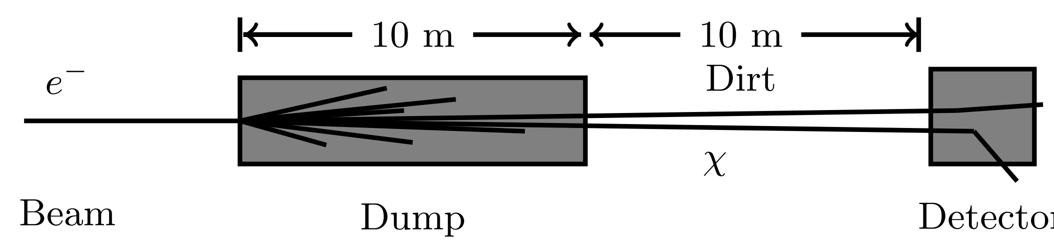
New DM Searches

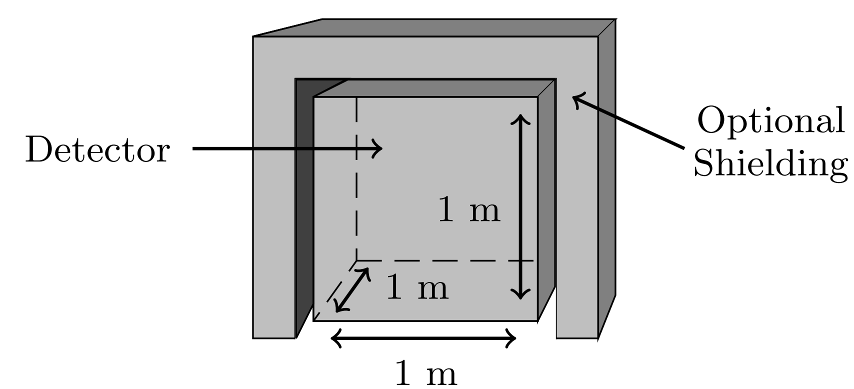
Light DM @ Electron Fixed Target Experiments

Eder Izaguirre, **GK**, Philip Schuster, Natalia Toro arXiv: 1411.1404 & 1505.00011

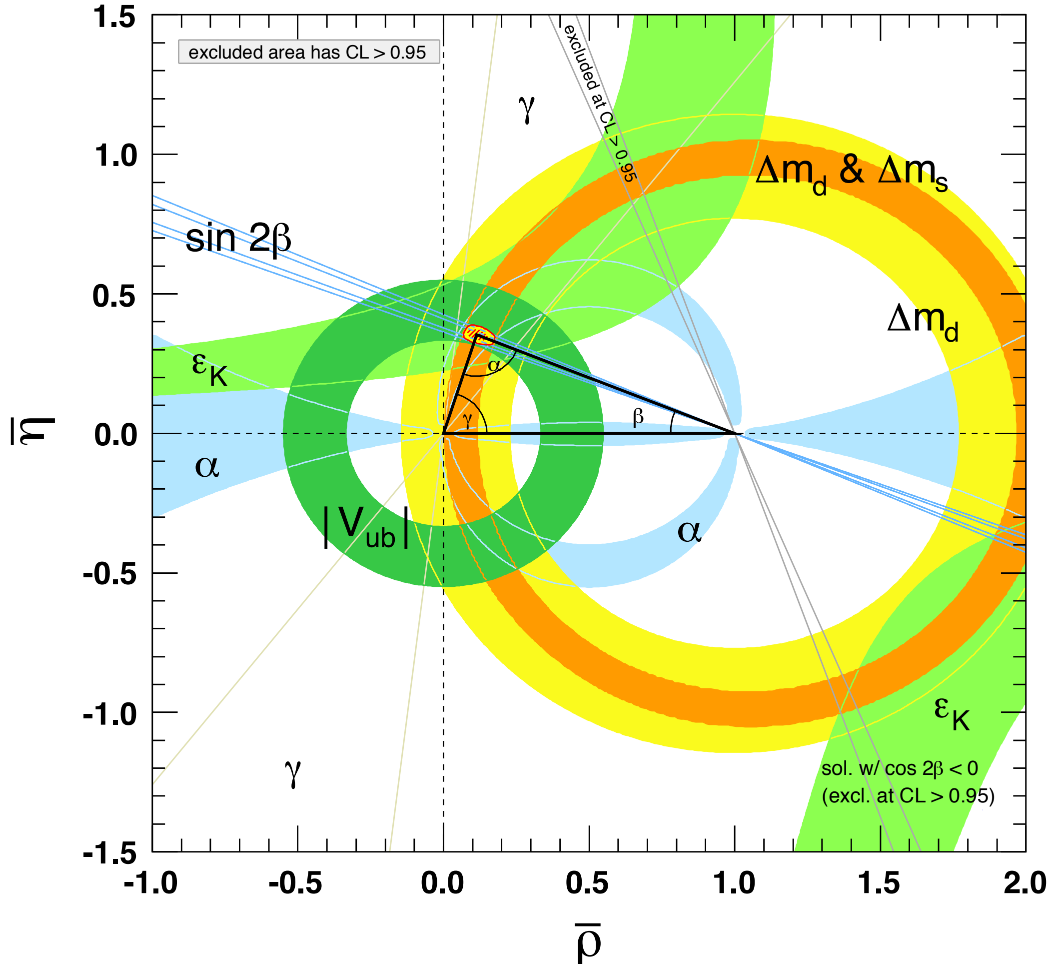


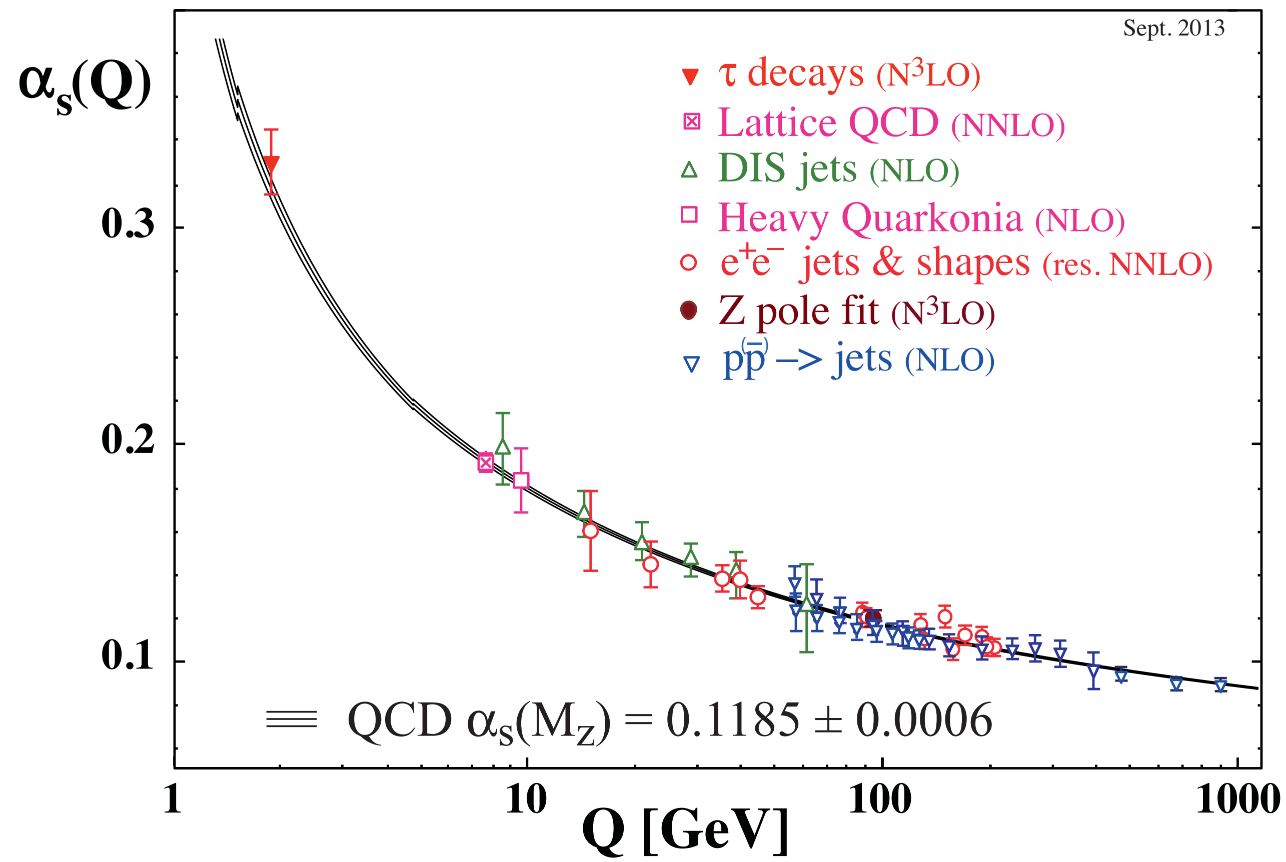






Lattice QCD





plots: PDG

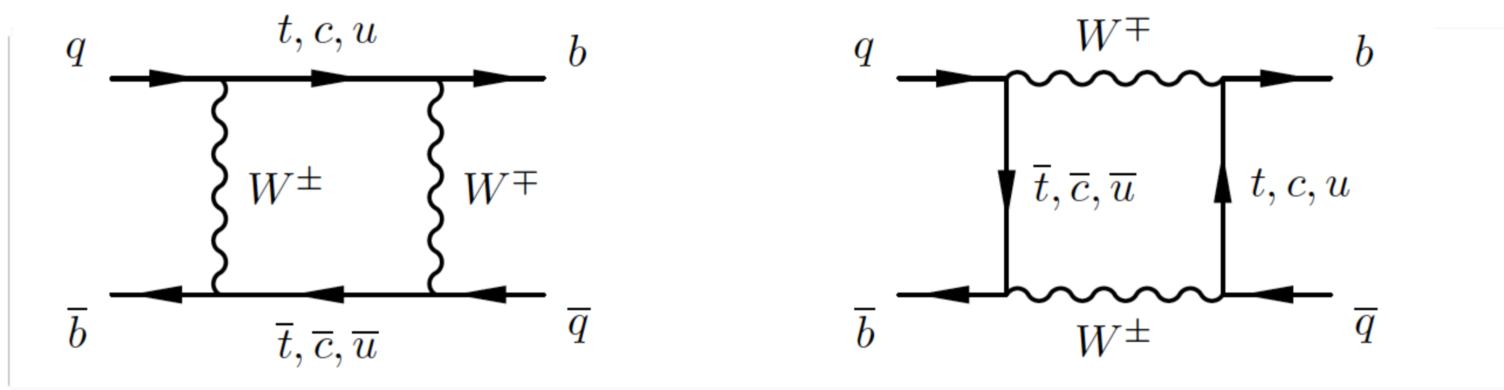
Supercomputer calculations of nonperturbative effects in QCD

$$\langle \mathcal{O}(U,q,\bar{q})\rangle = (1/Z)\int [dU]\prod_f [dq_f][d\bar{q}_f]\mathcal{O}(U,q,\bar{q})e^{-S_g[U]-\sum_f \bar{q}_f(D[U]+m_f)q_f}$$

FNAL: Andreas Kronfeld, Ruth van de Water, Paul Mackenzie, Ran Zhou

Lattice QCD & CKM Flavor

Hadronic matrix elements for $B - \bar{B}$ mixing in 3 flavor QCD



$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} C_i \mathcal{O}_i^q + \sum_{i=1}^{3} \tilde{C}_i \tilde{\mathcal{O}}_i^q,$$

$$\left\{ \begin{aligned}
\mathcal{O}_1^q &= \bar{b}^\alpha \gamma_\mu L q^\alpha \, \bar{b}^\beta \gamma_\mu L q^\beta, \\
\mathcal{O}_2^q &= \bar{b}^\alpha L q^\alpha \, \bar{b}^\beta L q^\beta, \\
\mathcal{O}_3^q &= \bar{b}^\alpha L q^\beta \, \bar{b}^\beta L q^\alpha, \\
\mathcal{O}_4^q &= \bar{b}^\alpha L q^\alpha \, \bar{b}^\beta R q^\beta, \\
\mathcal{O}_5^q &= \bar{b}^\alpha L q^\beta \, \bar{b}^\beta R q^\alpha, \\
\tilde{\mathcal{O}}_1^q &= \bar{b}^\alpha \gamma_\mu R q^\alpha \, \bar{b}^\beta \gamma_\mu R q^\beta, \\
\tilde{\mathcal{O}}_2^q &= \bar{b}^\alpha R q^\alpha \, \bar{b}^\beta R q^\beta, \\
\tilde{\mathcal{O}}_3^q &= \bar{b}^\alpha R q^\beta \, \bar{b}^\beta R q^\alpha,
\end{aligned} \right.$$

Calculate CKM ratio

Test of unitarity triangle

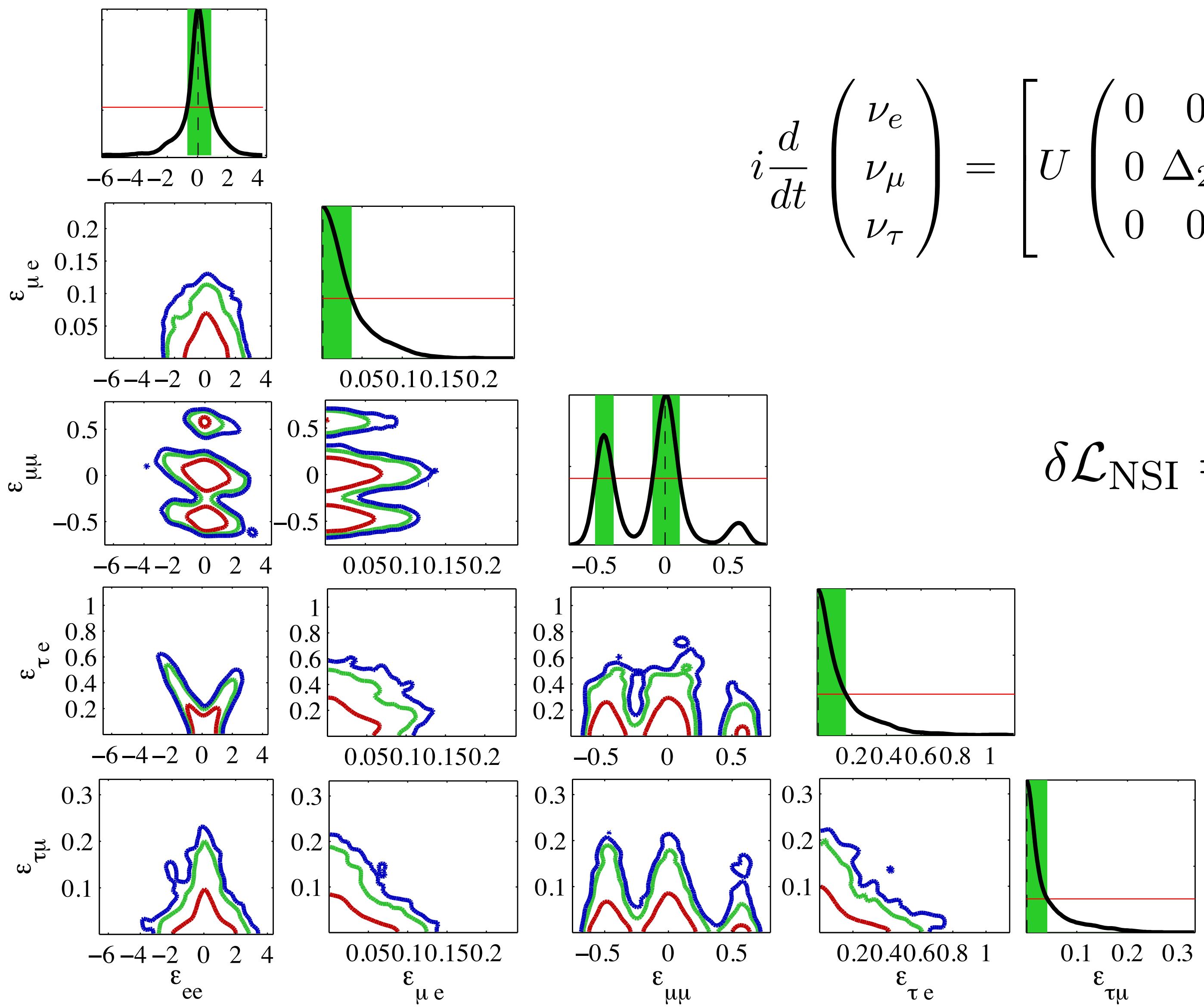
$$\left| \frac{V_{td}}{V_{ts}} \right|^2$$

arXiv:1602.03560 Fermilab Lattice + MILC

Neutrino Interactions

NonStandard Interactions (NSI) @ DUNE

Pilar Coloma arXiv: 1511.06357



$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta_{21} & 0\\ 0 & 0 & \Delta_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\delta\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F\sum_{f,P}\epsilon_{\alpha\beta}^{fP}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\overline{f}\gamma_\mu P f\right)$$

NSI effects propagating through Earth modify oscillation rates

Strong CP Problem

QCD allows CP-violating "theta-term" , but its effects are not observed

$$\mathcal{L}_{CPV} = \frac{\Theta}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu}, \quad (\Theta_{\text{exp.}} < 10^{-10}, \text{neutron EDM})$$

Popular solution: light new "axion" field , also modifies QED

$$\frac{g_a}{4}\int d^4x \left(\frac{a}{f_a}\right) F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g_a \int d^4x \left(\frac{a}{f_a}\right) \vec{E}\cdot\vec{B}$$

If it's abundant in cosmos, it yields an oscillating EDM in electrons

Christopher Hill 1508.04083

$$P_{tot} = \frac{1}{12\pi} g_a^2 m_a^4 \theta_0^2 \mu_{\text{Bohr}}^2.$$

also proposes new radiation observables in magnetized systems

Precision QCD calculations

Predictions for LHC diphoton production @ NNLO in QCD

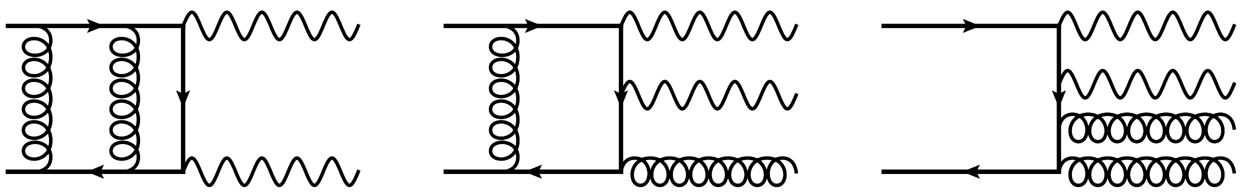
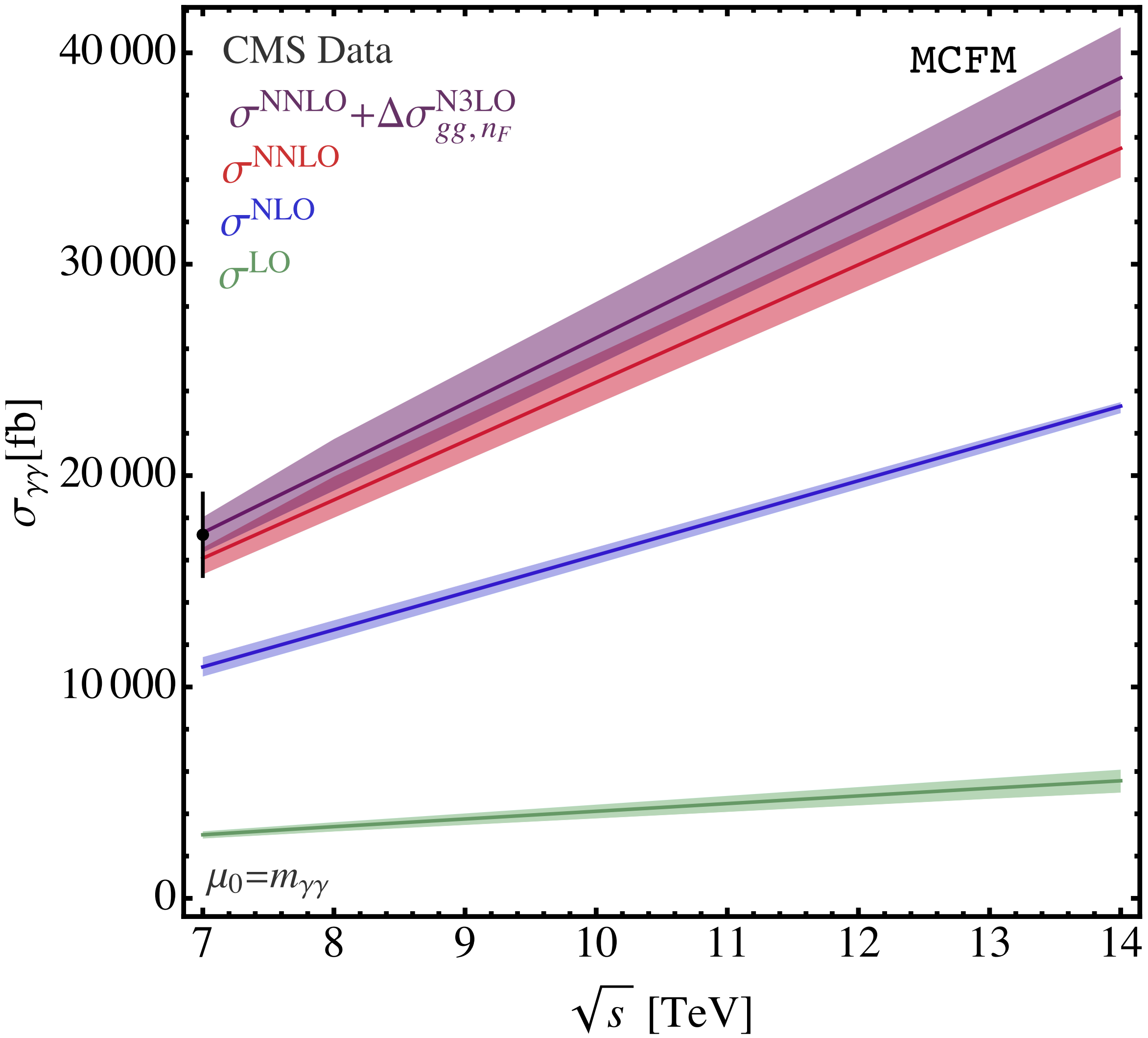


Figure 1. Representative Feynman diagrams for the calculation of $pp \to \gamma\gamma$ at NNLO. From left to right these correspond to double virtual (calculated in ref. [57]), real-virtual and real-real corrections.



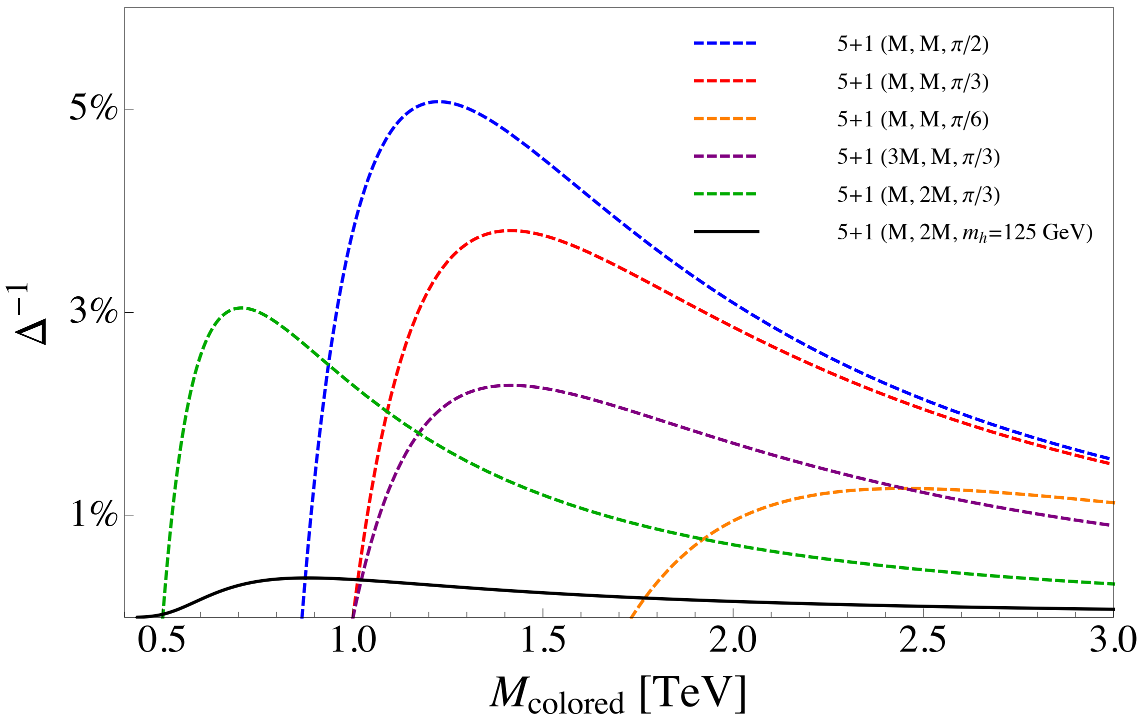
John Campbell, Keith Ellis, Ye Li, Ciaran Williams

arXiv: 1603.02663

Nature of EWSB

Tadpole Induced EWSB and pNGB Higgs Models

Roni Harnik, Kiel Howe, John "Jack" Kearney arXiv: 1603:03772



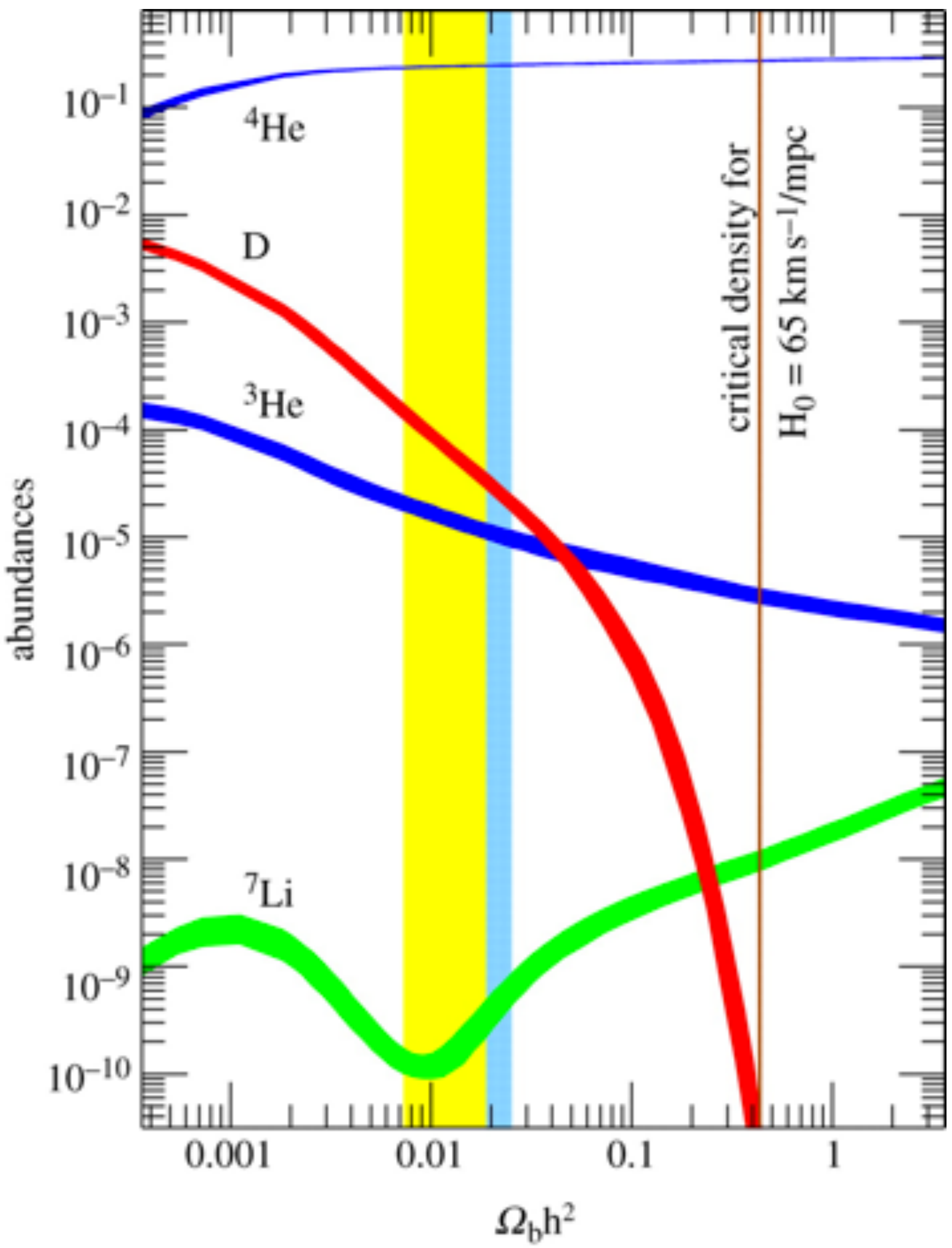
Example: composite Higgs with extra color charged particles

Higgs is approximate Nambu-Goldstone boson of global symmetry grp.

Higgs always has + mass, EWSB occurs in other sector

Reduced fine-tuning

Matter Asymmetry



Evidence for asymmetry

BBN & CMB

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

SM has right stuff to generate $\eta \neq 0$

Baryon number violation

Out of equilibrium universe

C & CP violation

(Sakharov 1967)

But *not enough*: need more ingredients

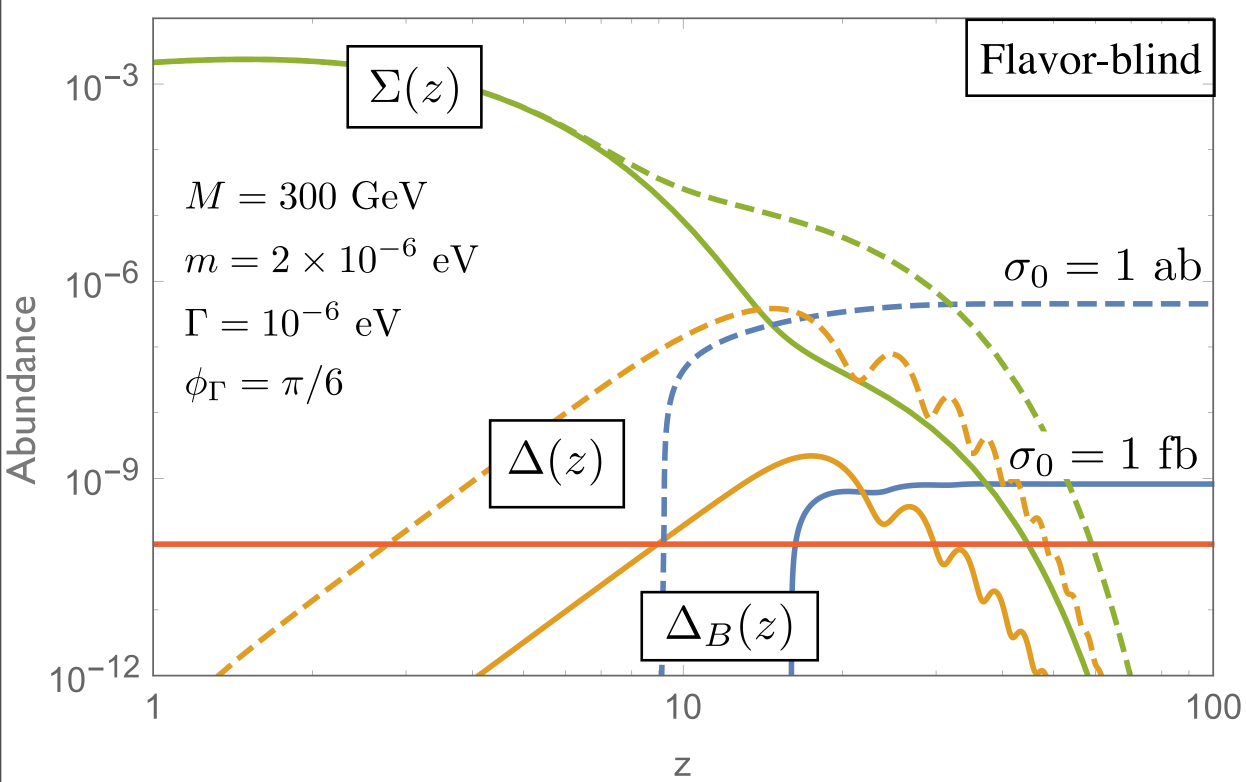
Many viable candidate theories, but very hard to test

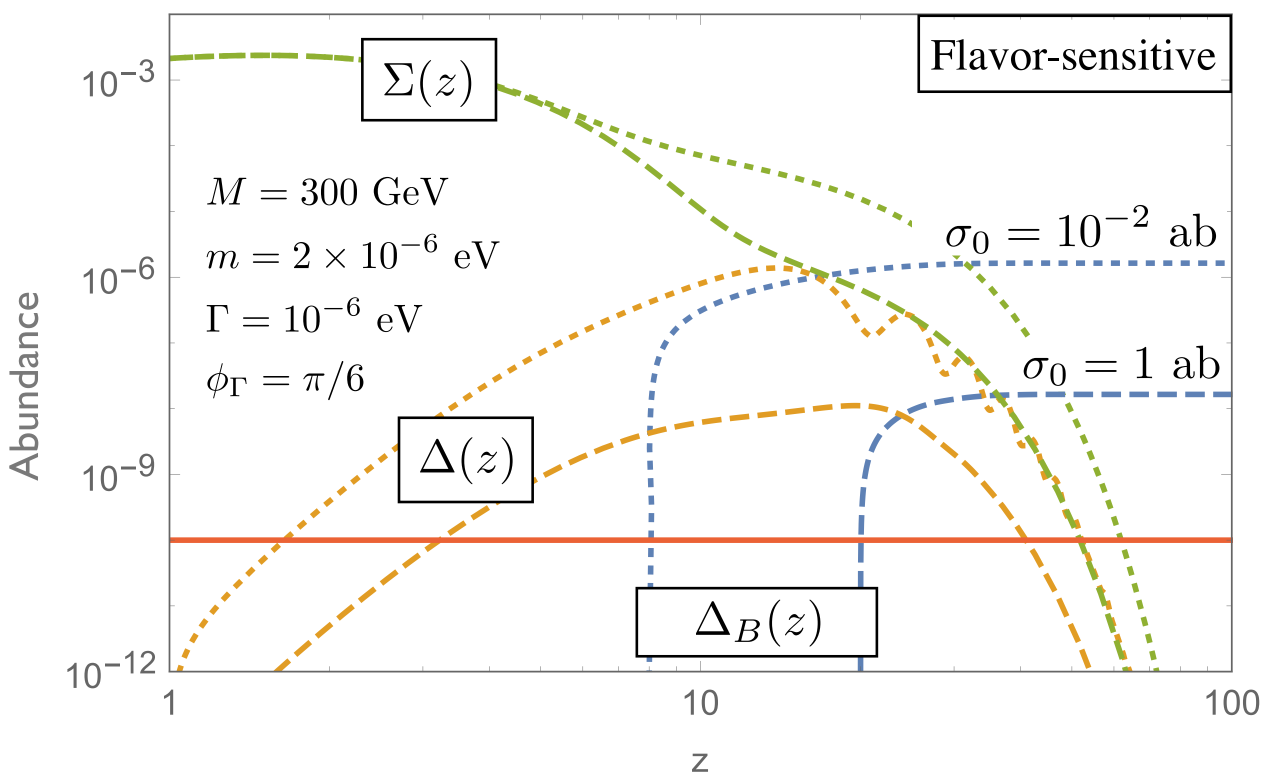
Matter Asymmetry

Baryogenesis via particle-antiparticle oscillations

Seyda Ipek, John March-Russell arXiv:1604.00009

$$-\mathcal{L}_{\rm mass} = M\chi\,\eta + \frac{1}{2}m_\chi\,\chi\,\chi + \frac{1}{2}m_\eta\,\eta\,\eta + \text{h.c.} \qquad \psi = \begin{pmatrix} \eta_\alpha \\ \chi^{\dagger\dot\alpha} \end{pmatrix}$$





Oscillations between beyond-SM states can enhance CP violating effects

Concluding Remarks

Identity of dark matter

Matter asymmetry

Nature of EWSB

Neutrino masses, mixings, interactions

Flavor puzzle (CKM structure)

Strong CP problem

FNAL theory: comprehensive, diversified portfolio of new ideas, new tools, and more precise calculations

Thanks!